

## LA-UR-12-24120

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Title: New analogies between extreme QCD and cold atoms

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Web



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title: "New analogies between extreme QCD and cold atoms"

abstract:

We discuss two new analogies between extreme QCD and cold atoms. One is the analogue of "hard probes" in cold atoms. The other is the analogue of "quark-hadron continuity" in cold atoms.



# New analogies between xQCD and cold atoms

Yusuke Nishida (LANL)

Extreme QCD 2012

August 21-23 (2012)



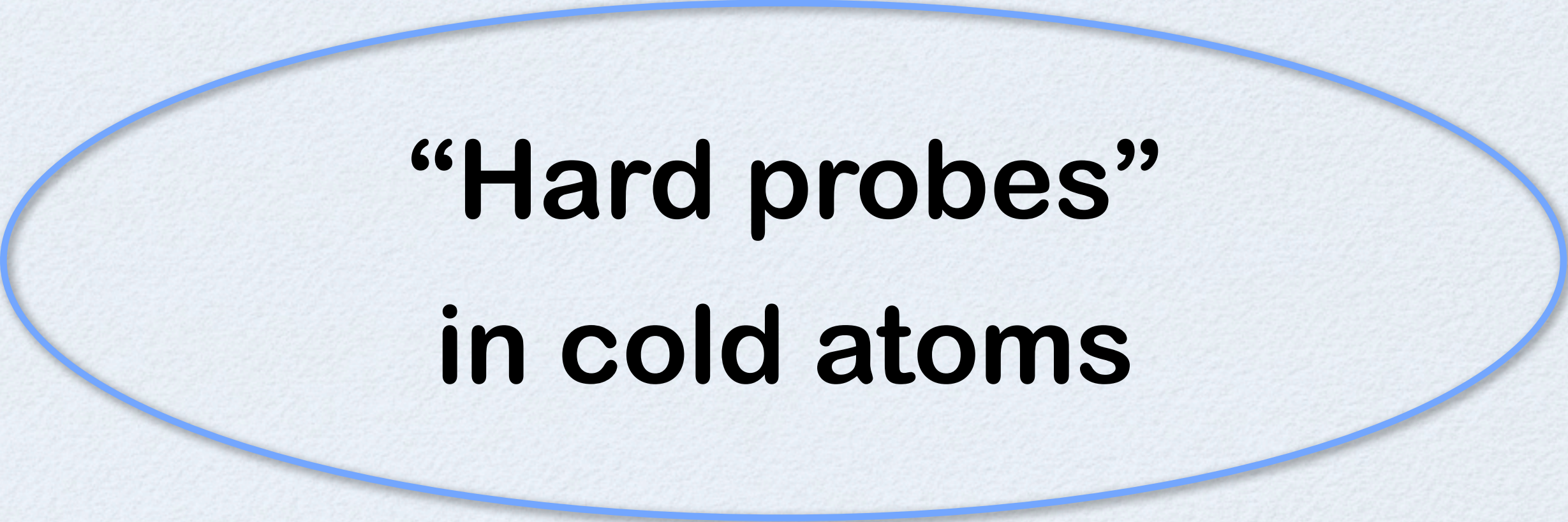
## 1. “Hard probes” in cold atoms

- Using energetic atoms to locally probe strongly-interacting atomic gases
- Y.N., Phys. Rev. A (2012) [arXiv:1110.5926]

## 2. “Quark-hadron continuity” in cold atoms

- Possible smooth connection between atoms and trimers in 3-component Fermi gases
- Y.N., arXiv:1207.6971



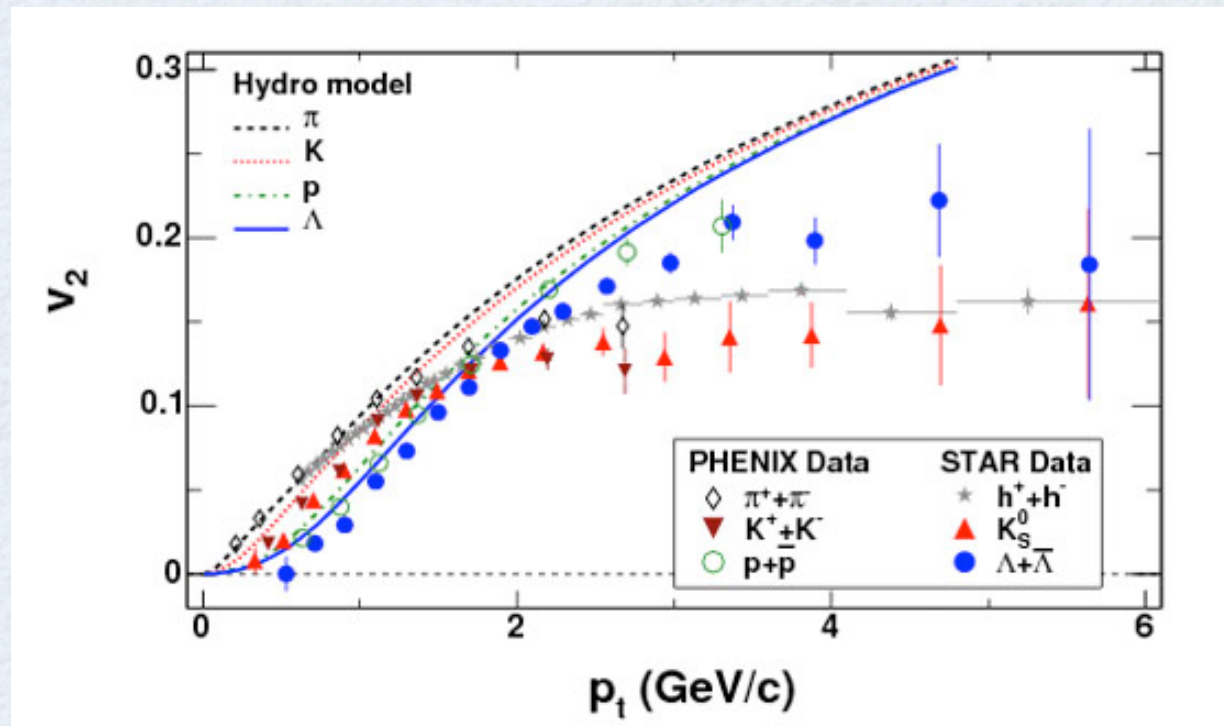


**“Hard probes”  
in cold atoms**



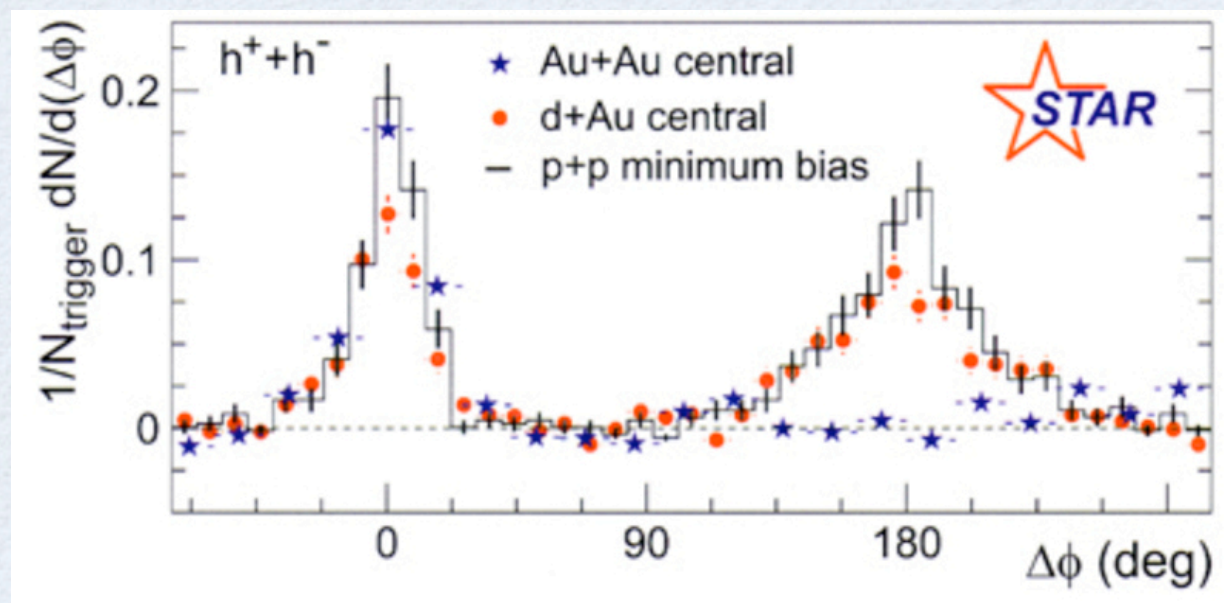
- Elliptic flow

- Small shear viscosity



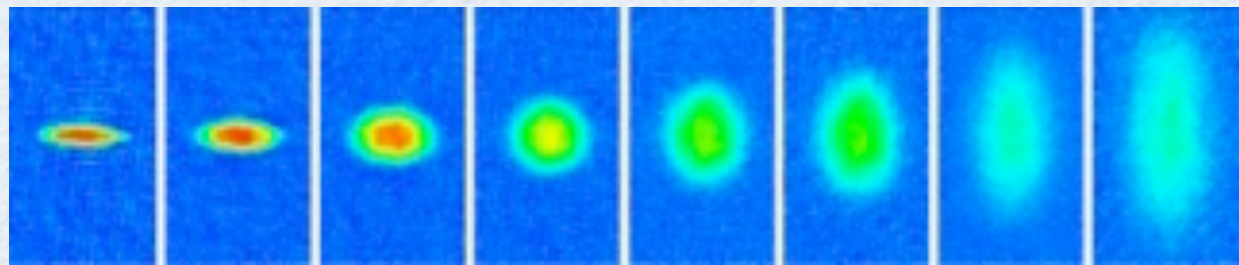
$$\frac{\eta}{s} \approx \frac{1}{4\pi}$$

- Jet quenching



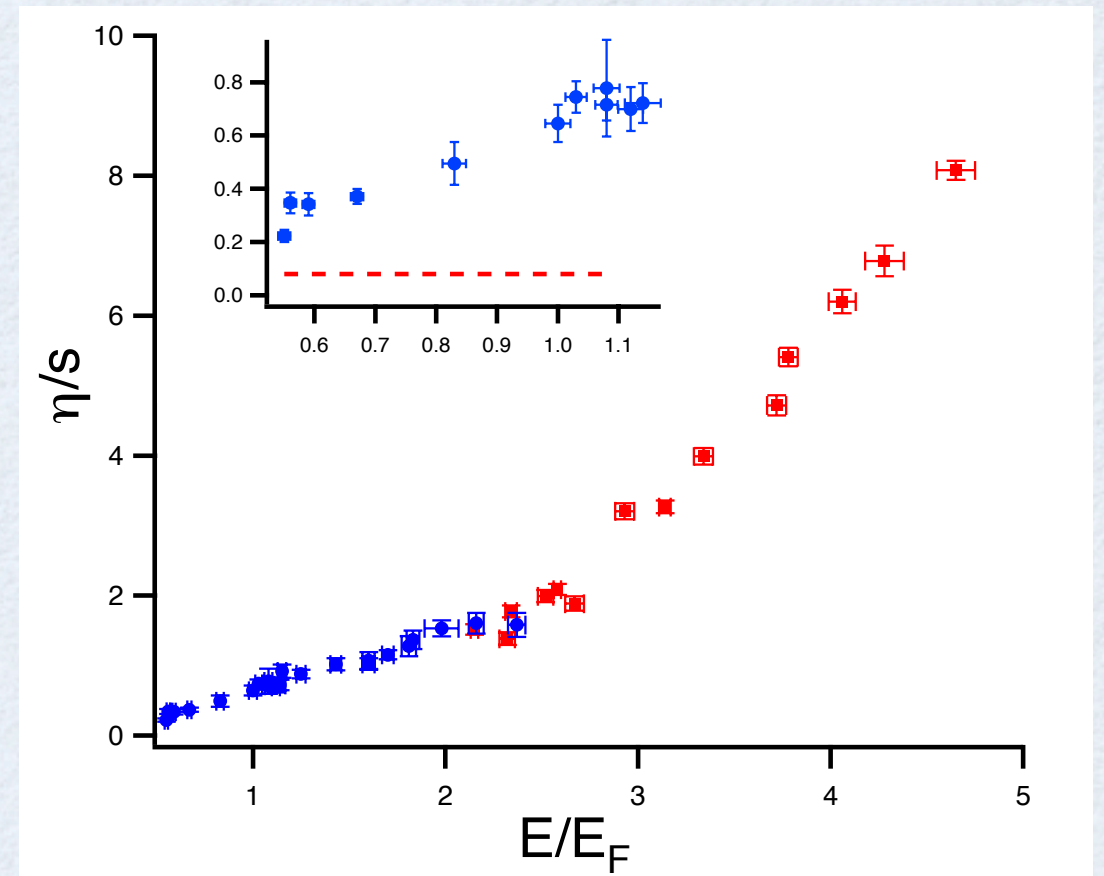


- Elliptic flow



K.M. O'Hara et al., Science (2002)

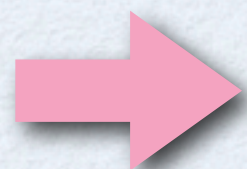
- Small shear viscosity



C. Cao et al., Science (2011)

- Jet quenching

???



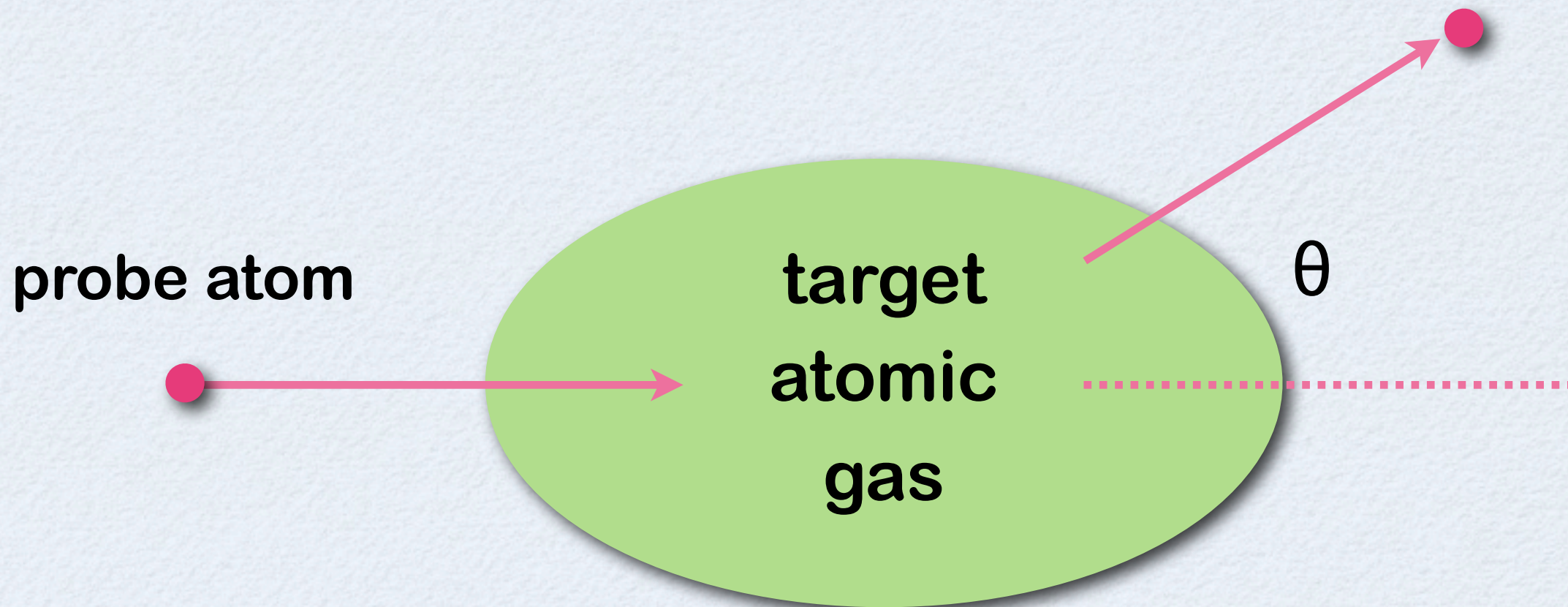
What is its analogue in cold atoms ?



# Probe atomic gas with atoms

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Shoot a probe **atom** into the target atomic gas and measure its differential scattering rate



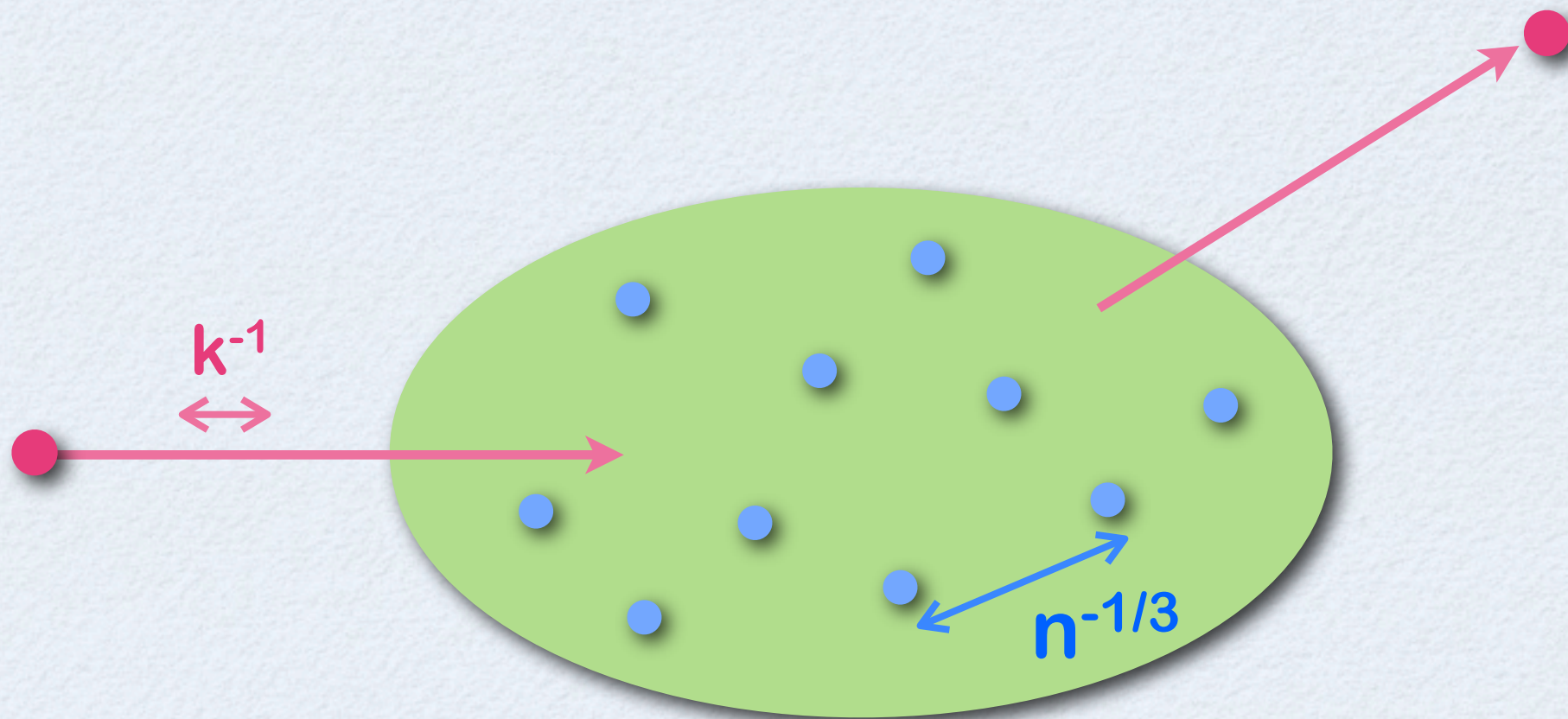
What can we learn from the scattering data on the (strongly-interacting) target atomic gas?



# Probe atomic gas with atoms

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Shoot a probe **atom** into the target atomic gas and measure its differential scattering rate



Large  $k \gg n^{1/3} \Rightarrow$  Few-body scattering problems

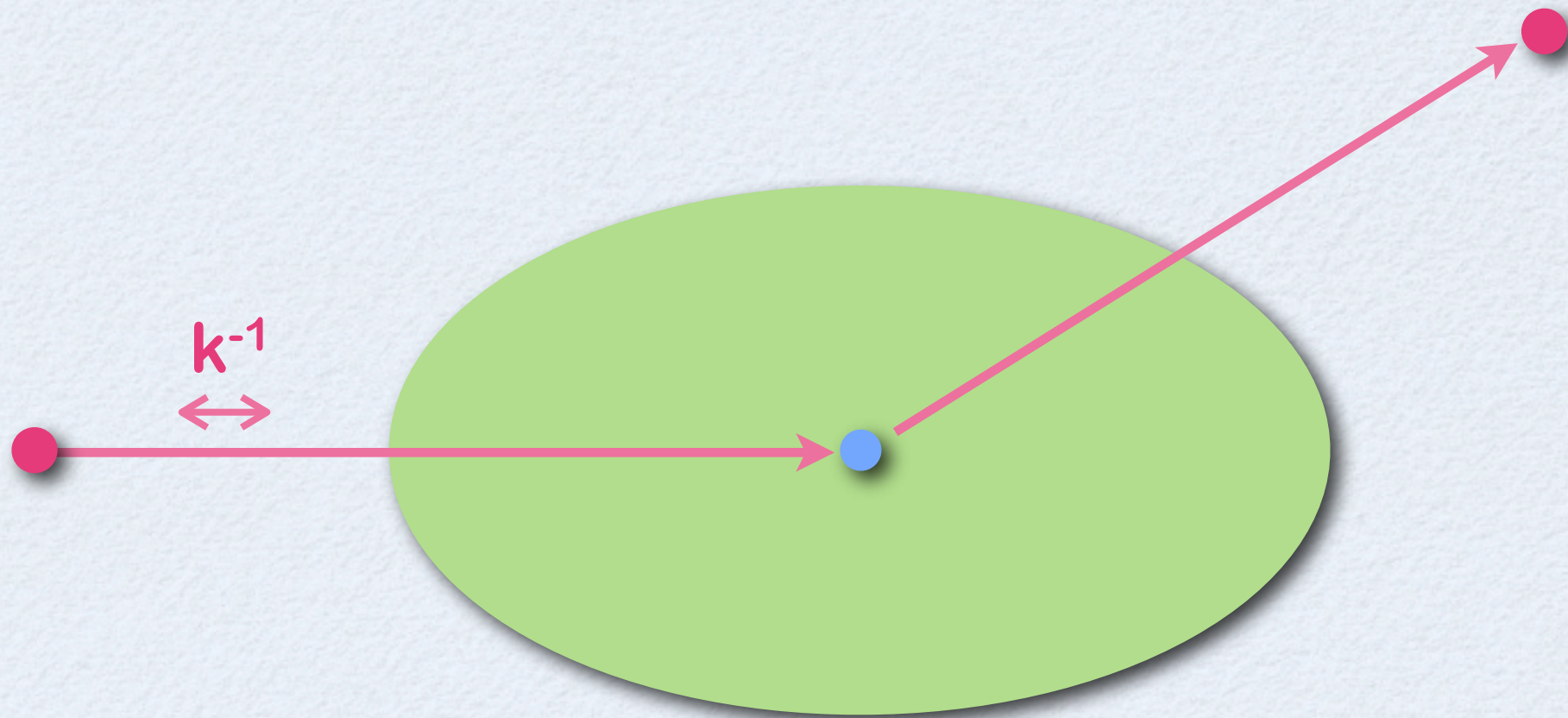
$$\frac{d\Gamma(k)}{d\Omega} = \dots$$



# Leading contribution

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Shoot a probe **atom** into the target atomic gas and measure its differential scattering rate



Large  $k \gg n^{1/3} \Rightarrow$  Few-body scattering problems

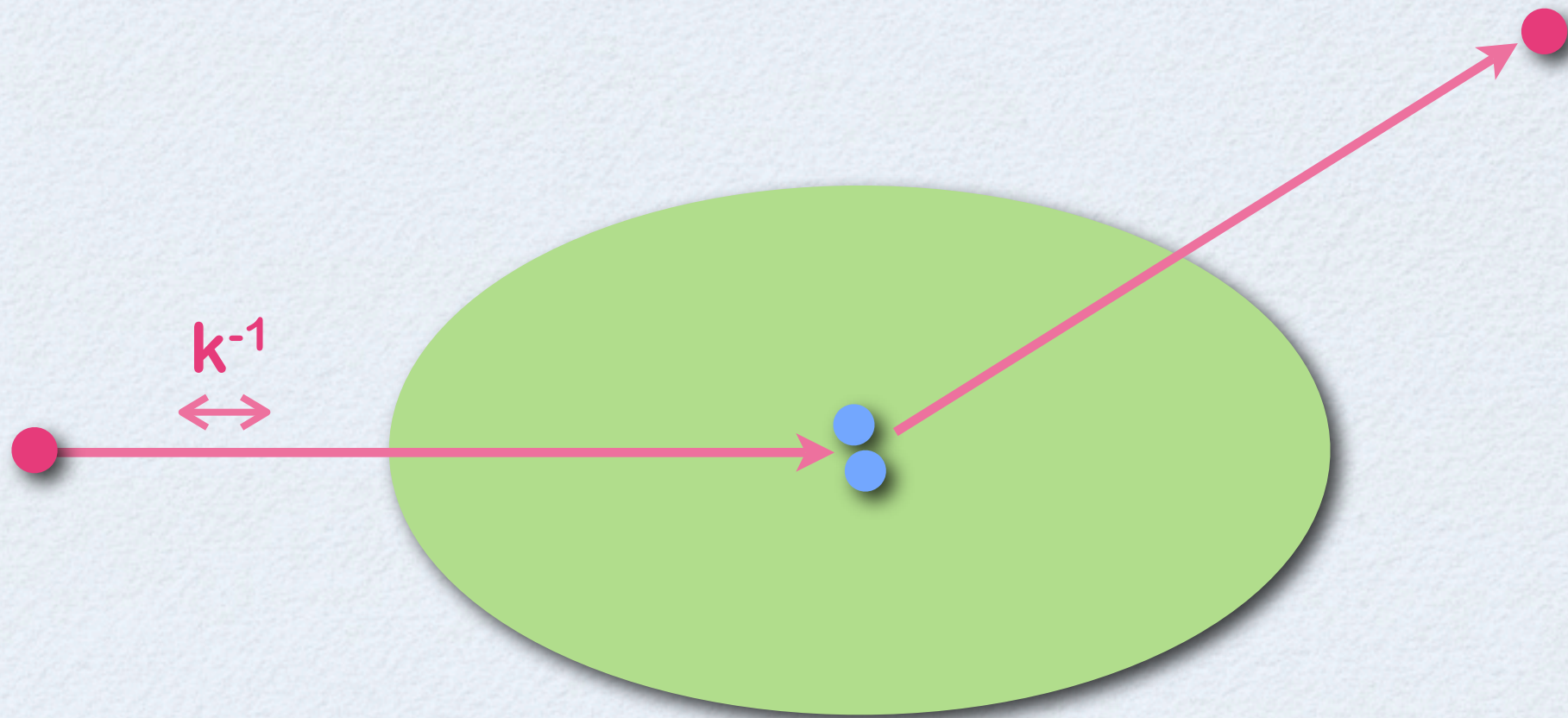
$$\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + \dots$$



# Sub-leading contribution

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Shoot a probe **atom** into the target atomic gas and measure its differential scattering rate



Large  $k \gg n^{1/3} \Rightarrow$  Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta) \frac{C}{k^2} + \dots$$

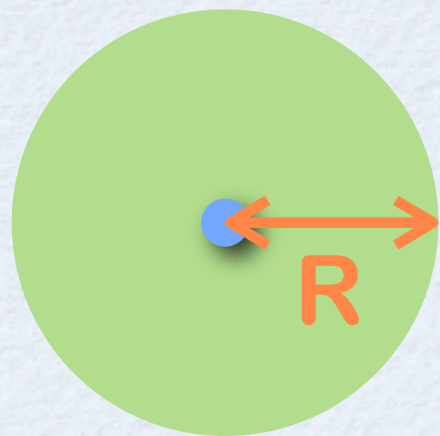


# What is “C” ?

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Probability of finding 2 particles at small separation

- noninteracting gas :  $\langle \hat{n}(r) \hat{n}(0) \rangle = n^2$
- interacting gas :  $\langle \hat{n}(r) \hat{n}(0) \rangle \rightarrow \frac{C}{(4\pi|r|)^2}$



→


$$\int_{|r| < R} \langle \hat{n}(r) \hat{n}(0) \rangle \sim \begin{cases} n^2 R^3 \\ C R \end{cases}$$

Anomalous enhanced probability is quantified by the “**contact density**” **C**

Important characteristic of strongly-int atomic gases



- scattering rate :  $\Gamma(k) = -2 \operatorname{Im} \Sigma(k)$
- optical theorem :  $\Gamma(k) = \int d\Omega \frac{d\Gamma(k)}{d\Omega}$


$$\begin{aligned} iG(k) &= \int dx e^{ikx} \langle T \psi(x) \psi^\dagger(0) \rangle \\ &= \sum_i A_i(k) \langle O_i \rangle \end{aligned}$$

$$n = \langle \psi^\dagger \psi \rangle, \quad C = \langle (\psi^\dagger \psi)^2 \rangle, \quad \dots$$

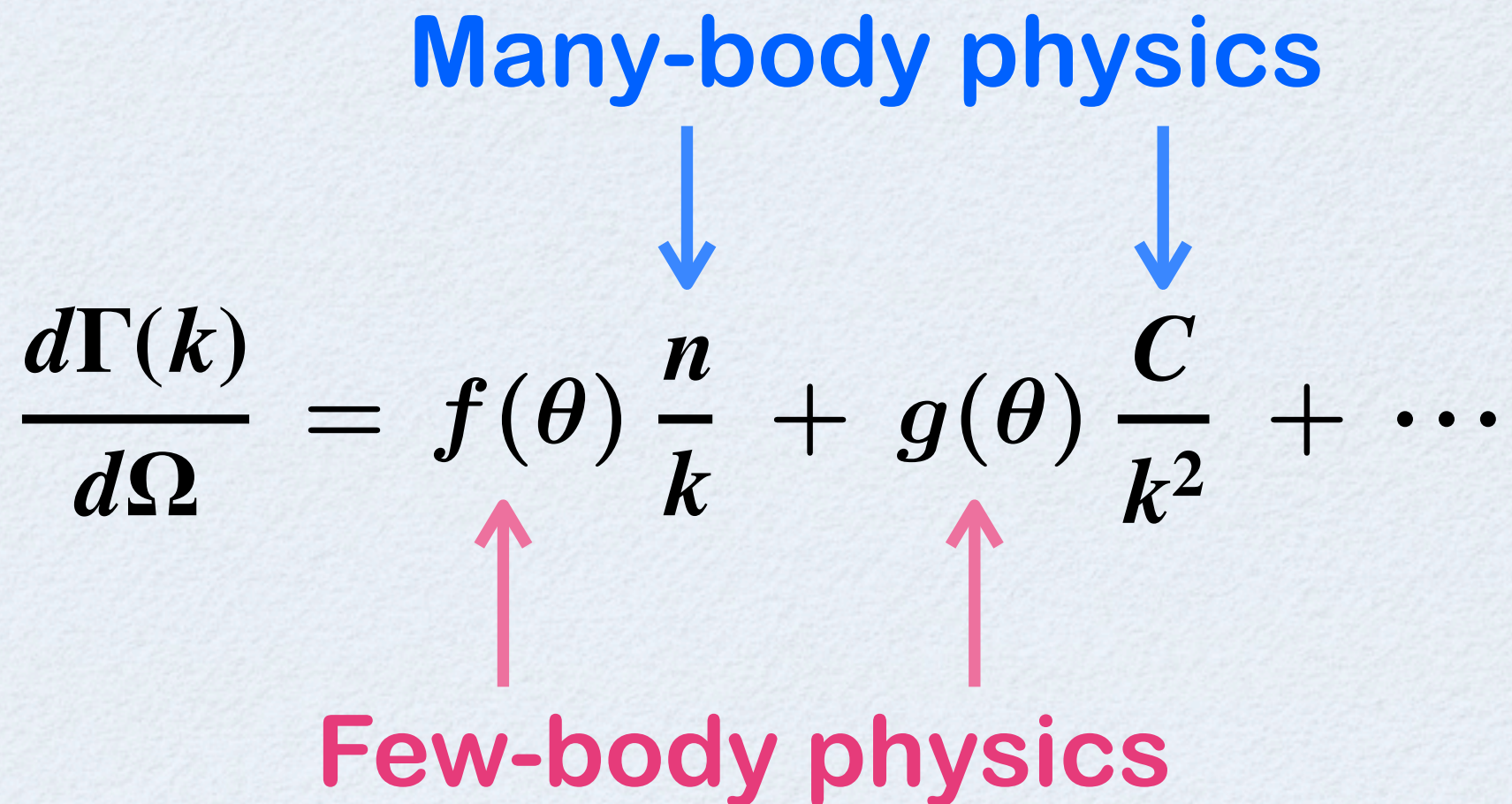
Lowest few  $O_i$  are needed at large  $k$



Systematic large- $k$  expansion !



**Many-body physics**



$$\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta) \frac{C}{k^2} + \dots$$

**Few-body physics**

**Few-body physics plays an important role  
to probe many-body physics !**



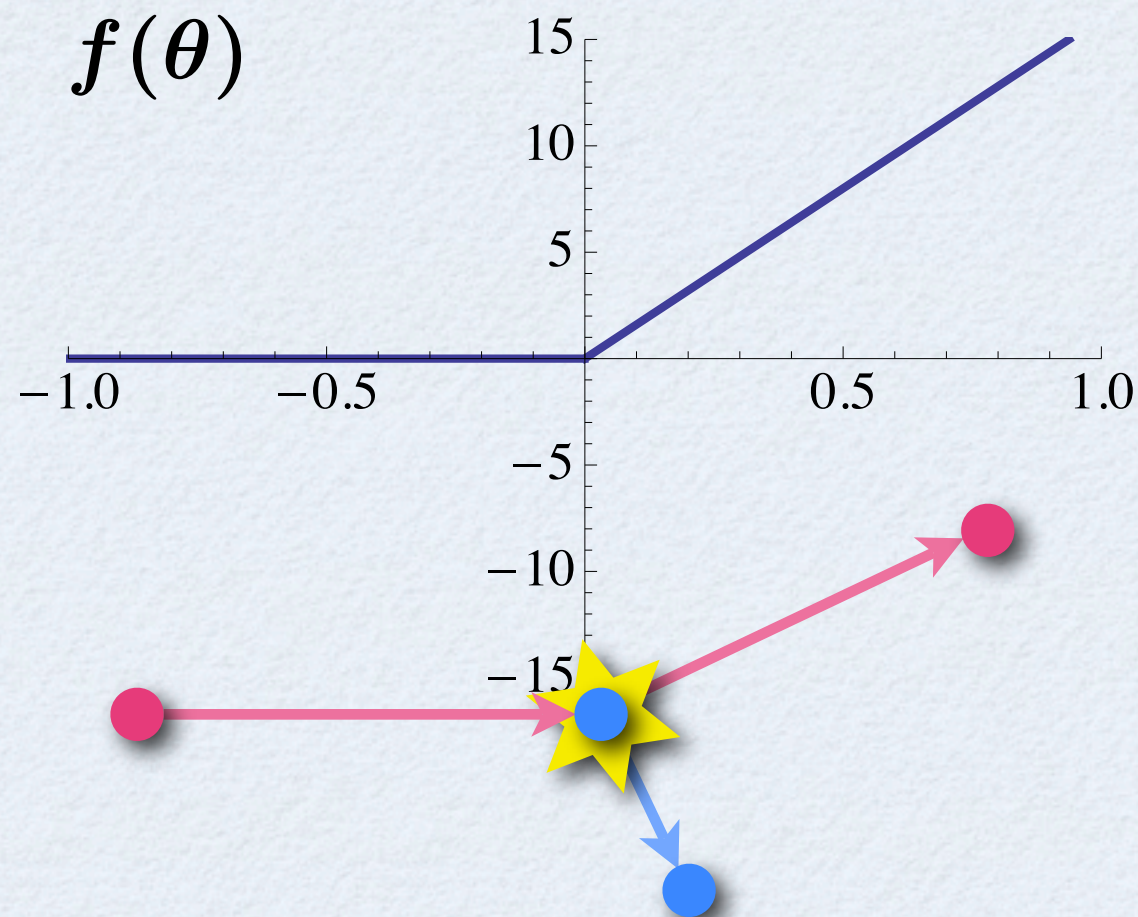
# Differential scattering rate

13/32

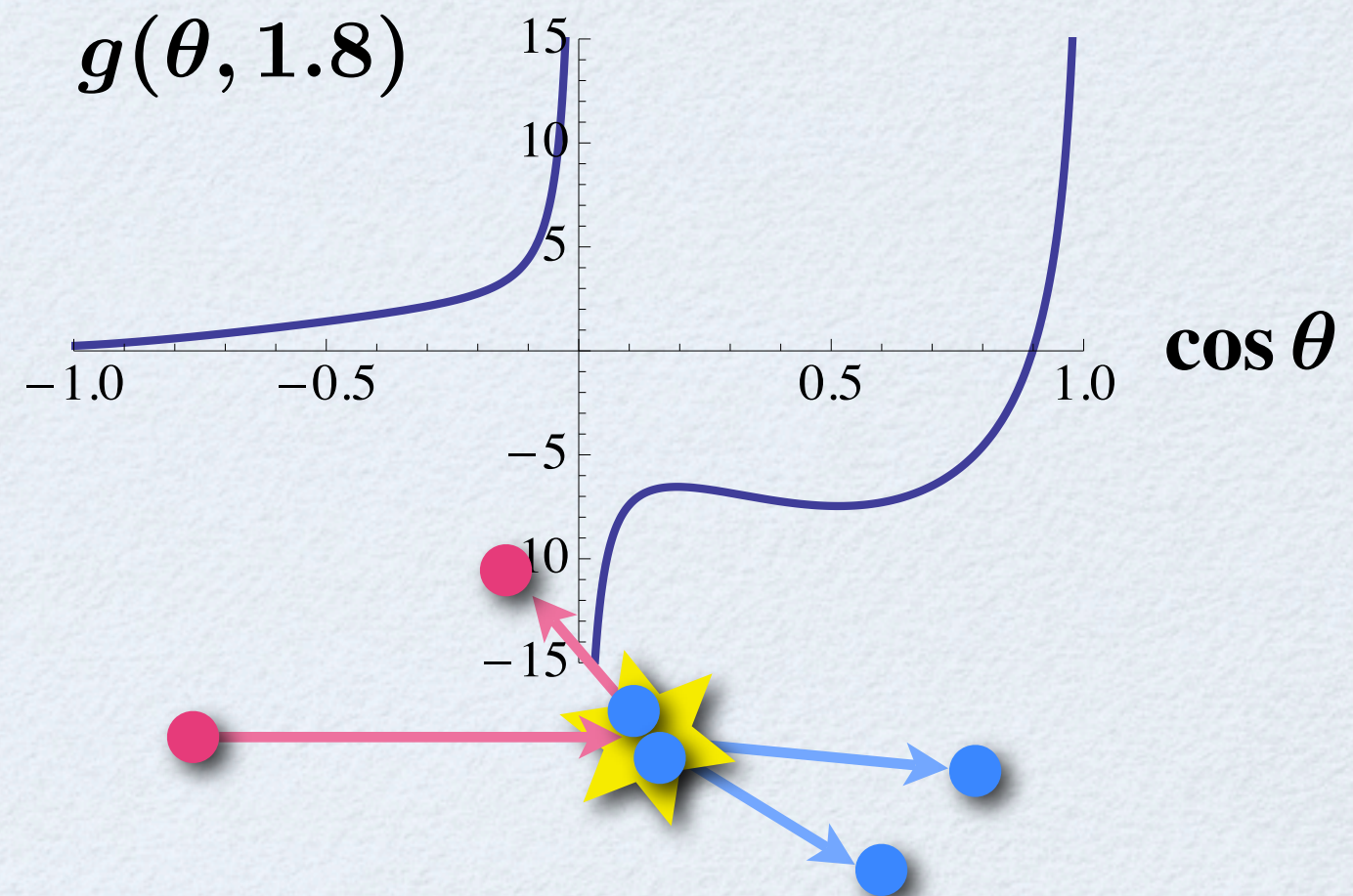
$$\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta, k/\kappa_*) \frac{C}{k^2} + \dots$$

For zero-range interactions

Efimov effect



forward scattering  
( $\theta < 90^\circ$ ) only



backward scattering  
( $\theta > 90^\circ$ ) possible



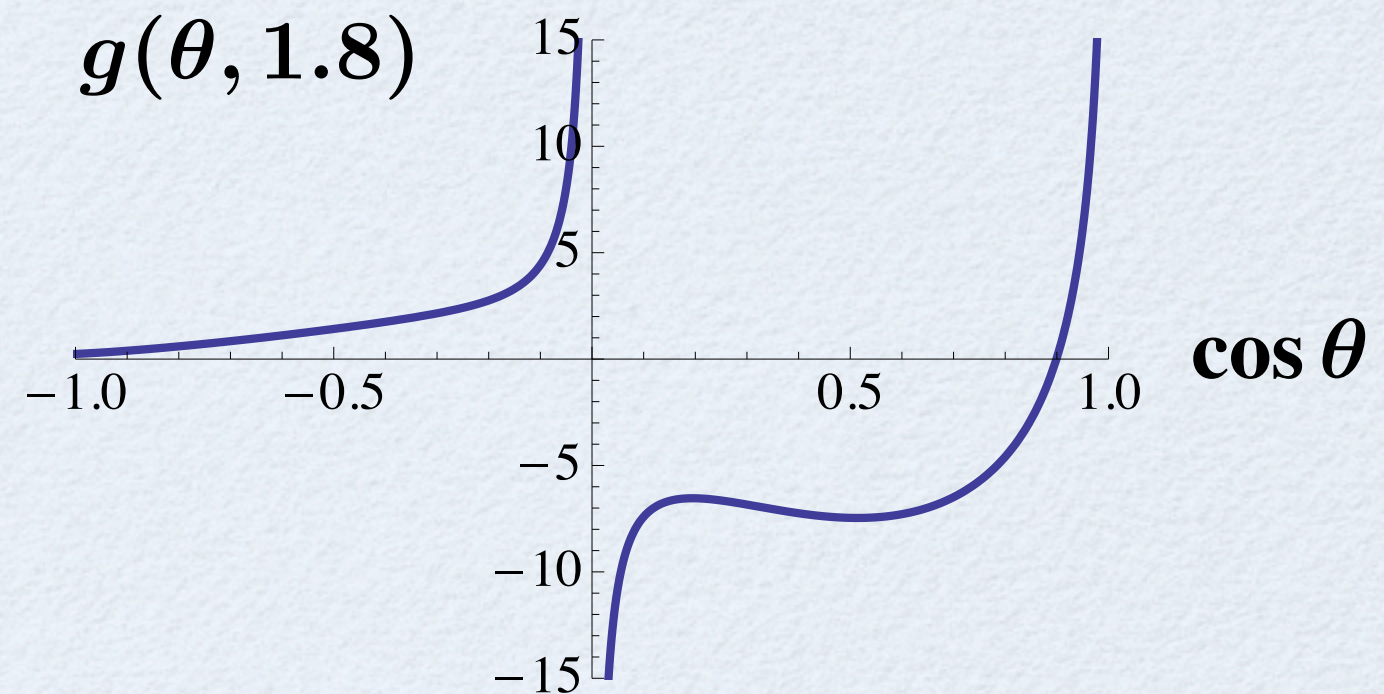
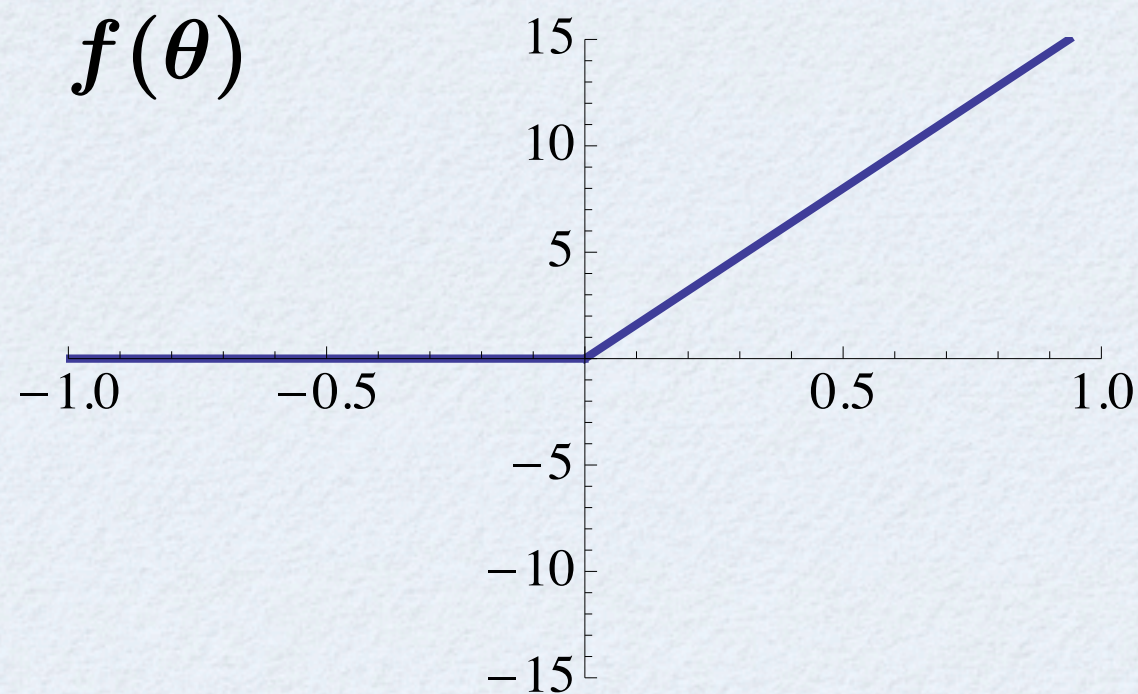
# Differential scattering rate

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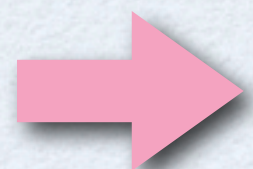
$$\frac{d\Gamma(k)}{d\Omega} = f(\theta) \frac{n}{k} + g(\theta, k/\kappa_*) \frac{C}{k^2} + \dots$$

For zero-range interactions

Efimov effect



Backward scattering rate measures contact density



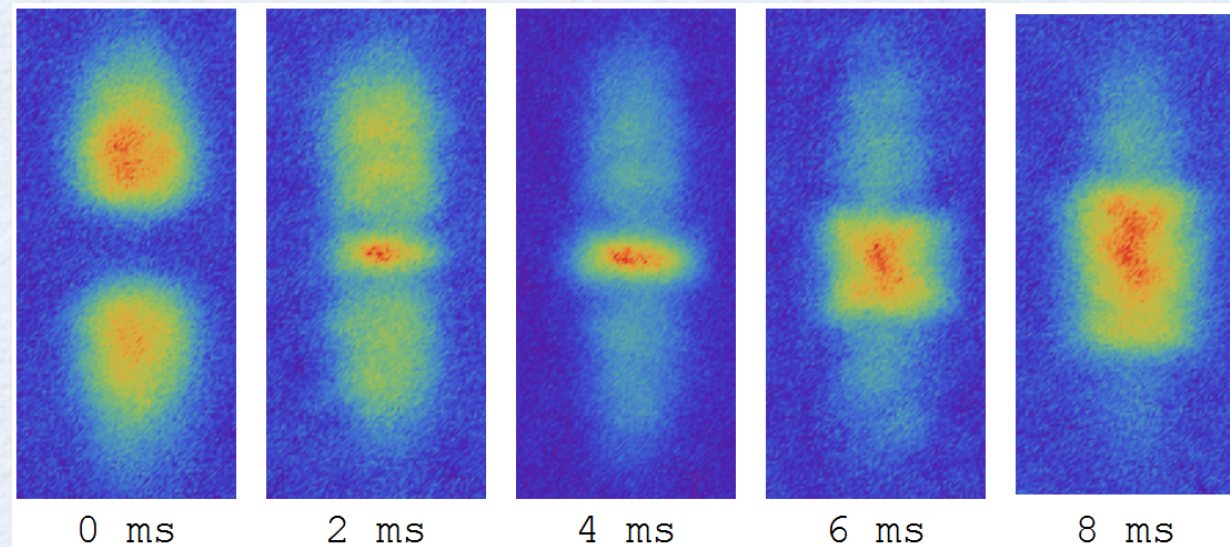
New local probe of strongly-int atomic gases



# Ultracold atom “colliders”

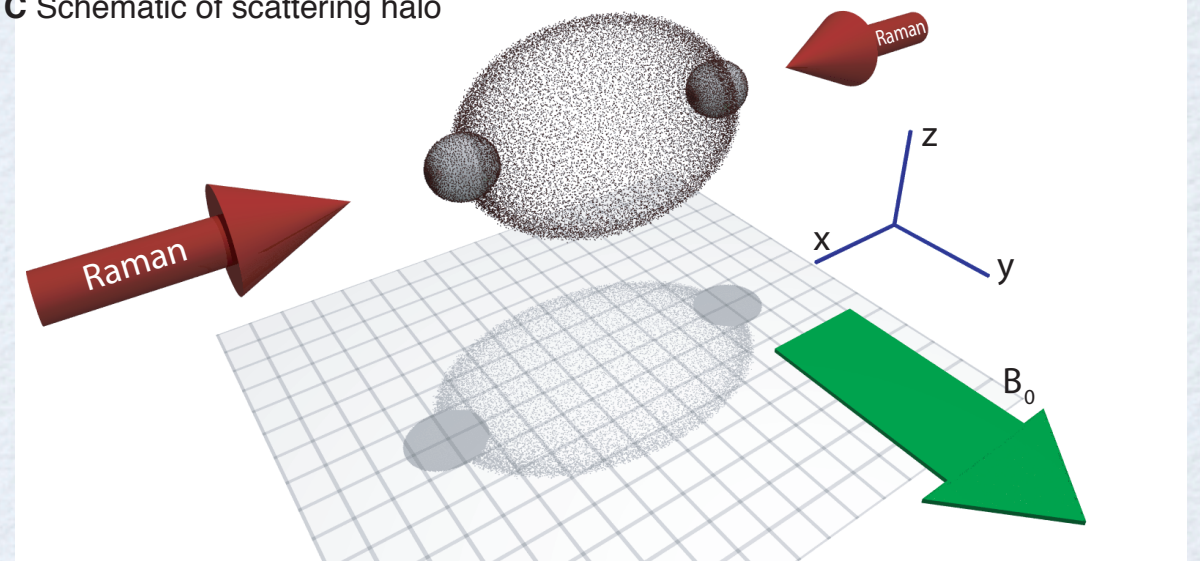
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## Duke (2011)

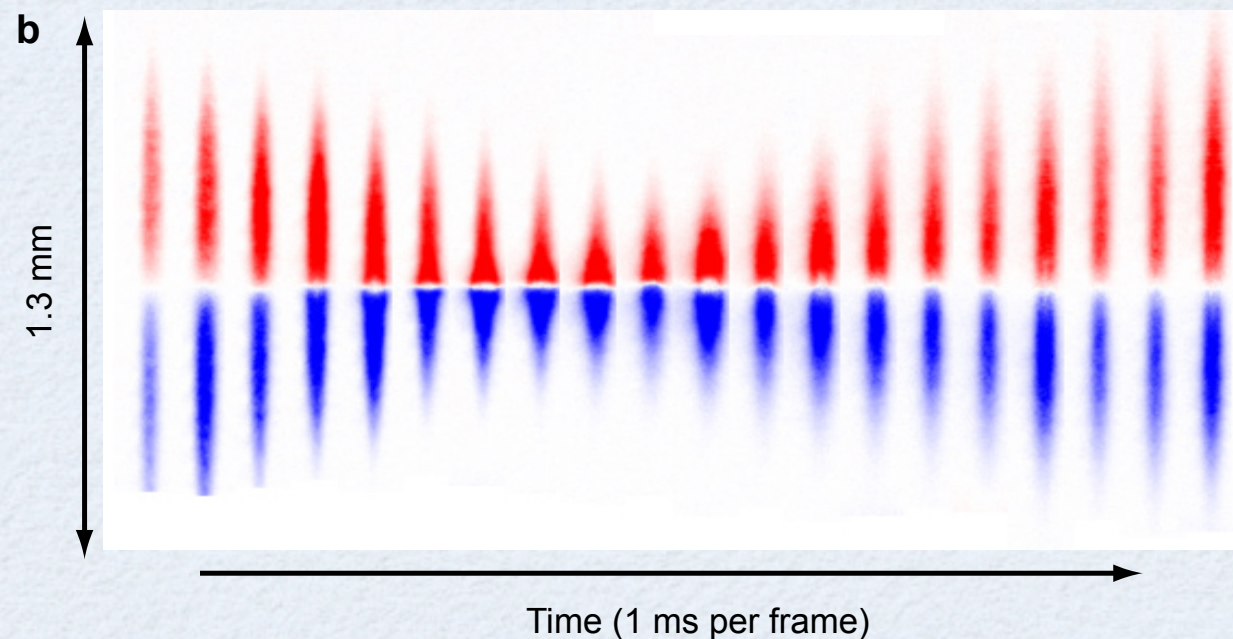


## NIST (2012)

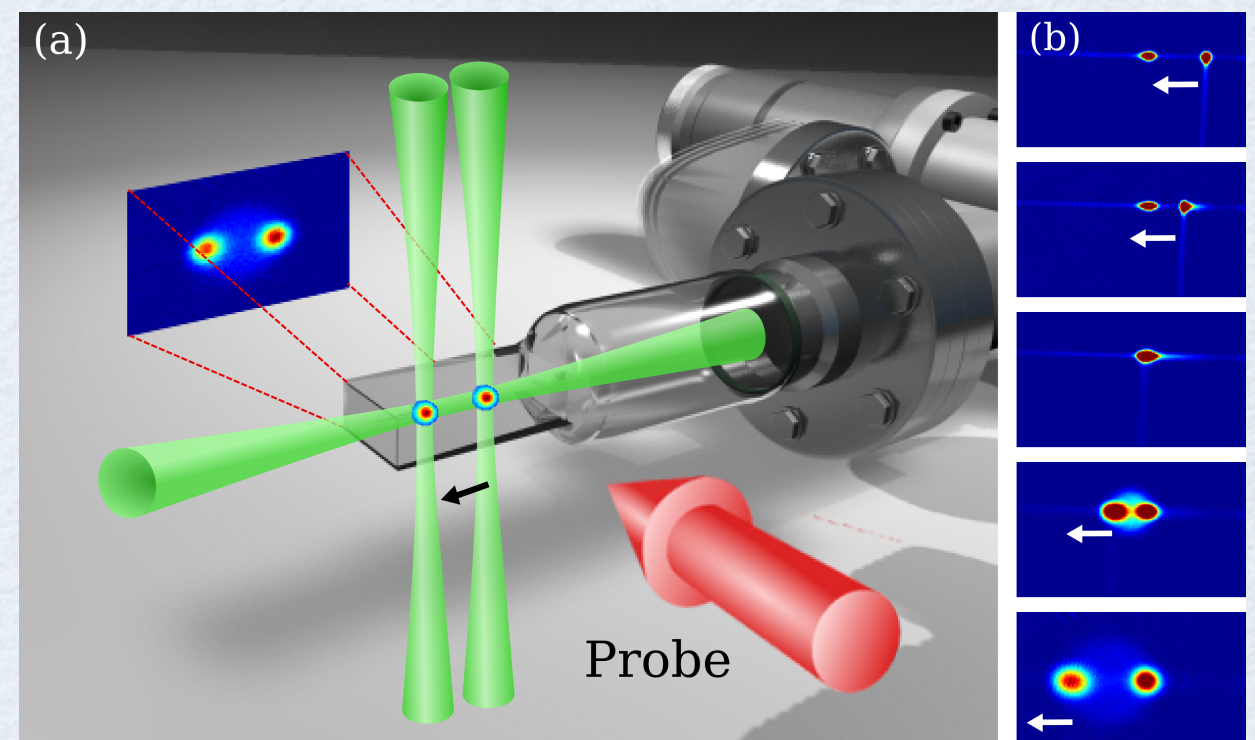
C Schematic of scattering halo



## MIT (2011)



## Otago (2012)

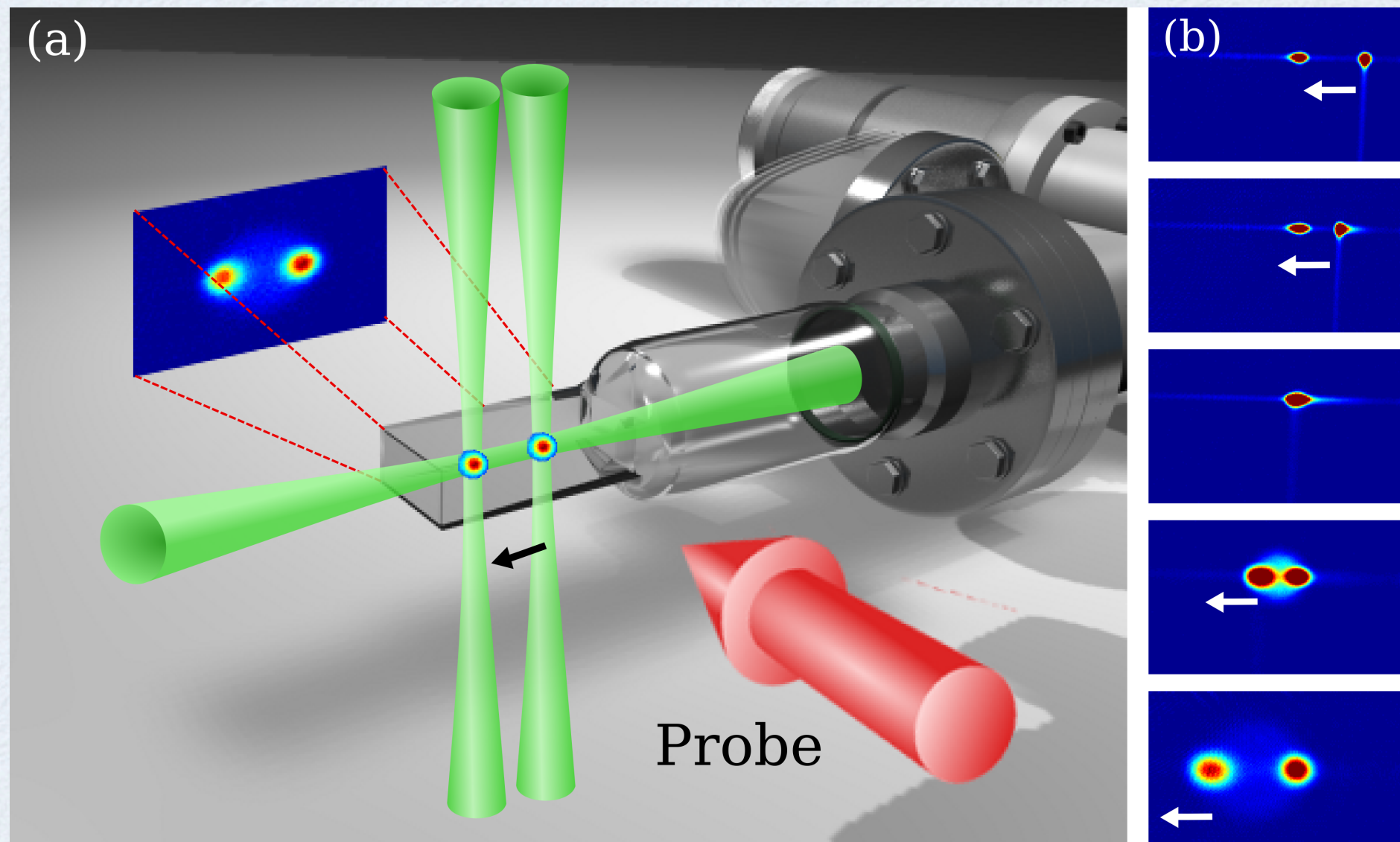




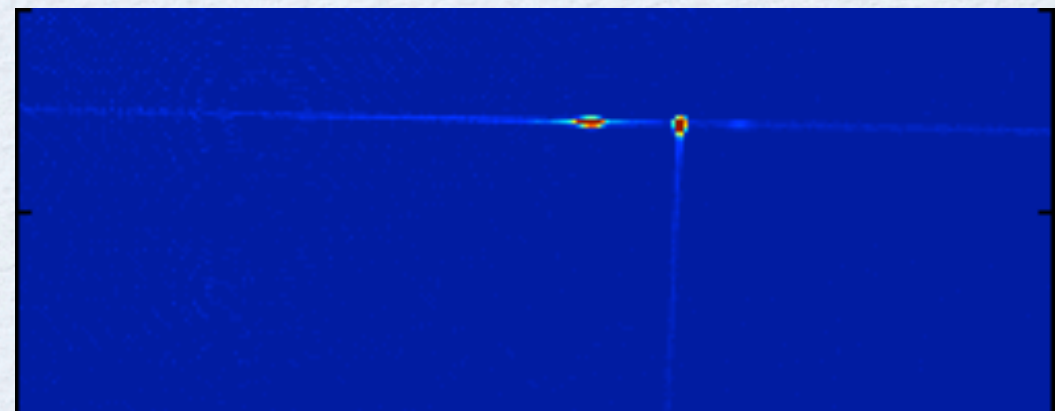
# Ultracold atom “colliders”

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“A laser based accelerator for ultracold atoms”



University of Otago  
(New Zealand)  
Optics Letters (2012)

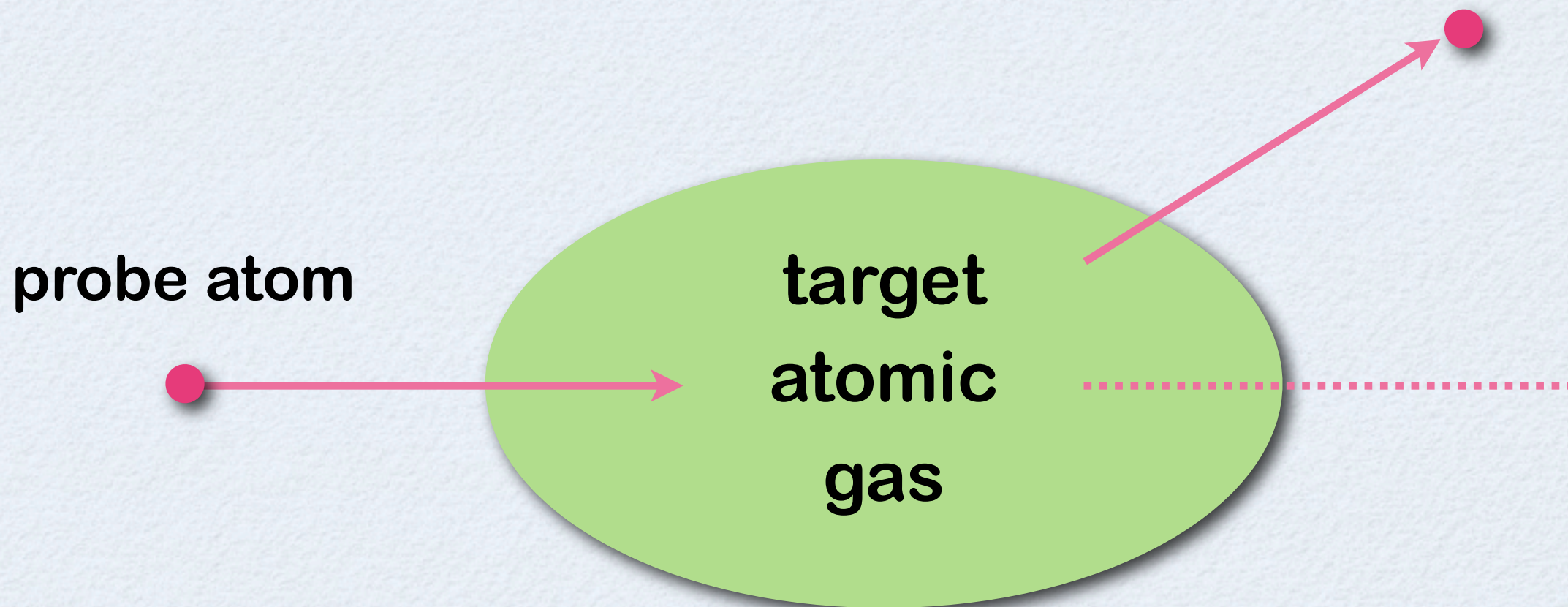




# Short summary 1

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- Energetic atoms  $\Rightarrow$  New tool to locally probe strongly-interacting atomic gases
- Systematic large- $k$  expansions are possible
  - ✓ backward scattering  $\Rightarrow$  contact density



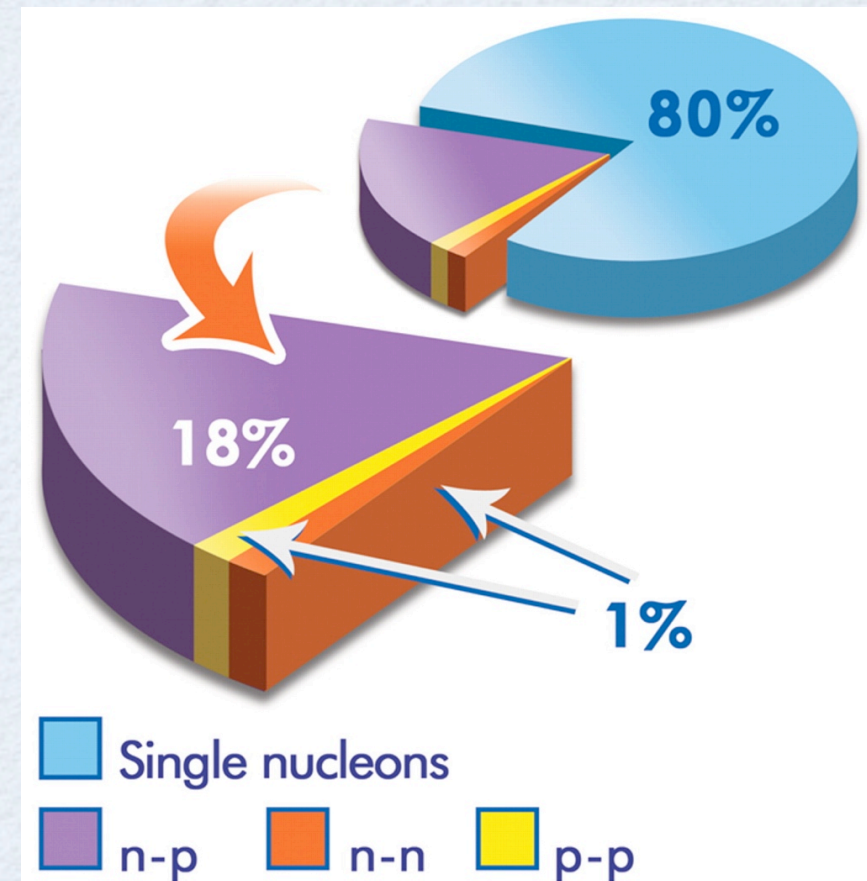
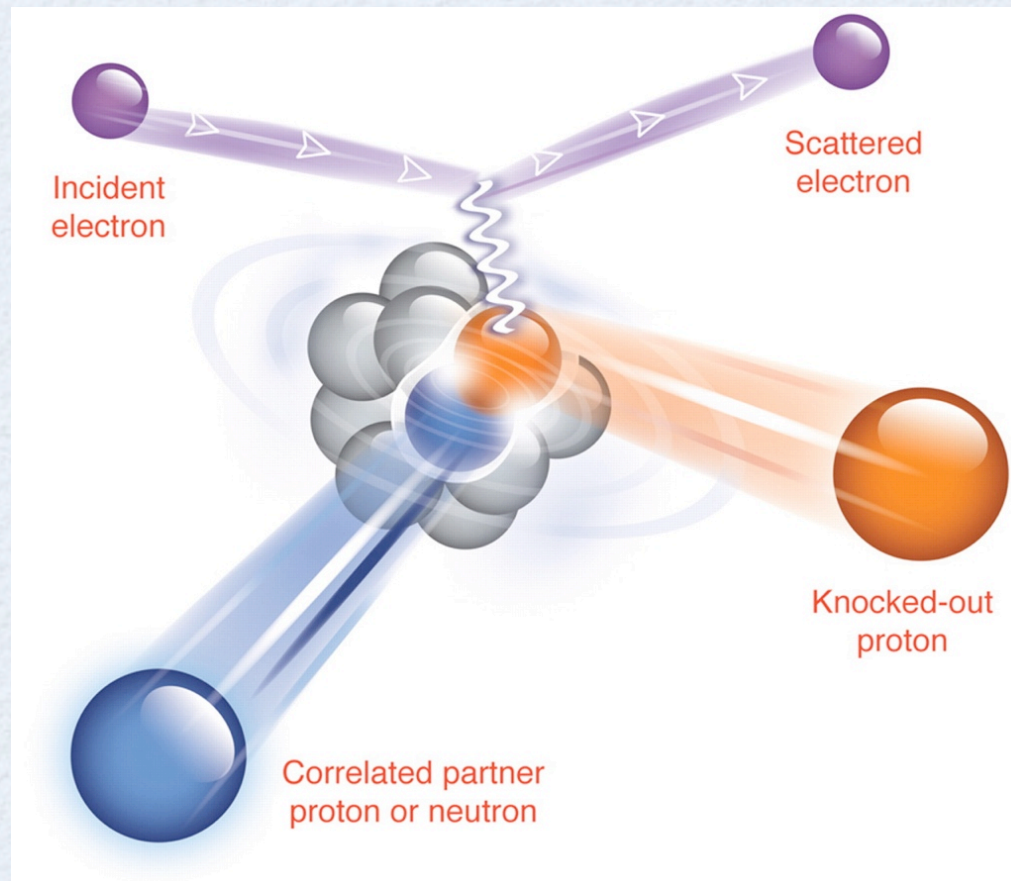


# Short summary 1

18/32

- Energetic atoms  $\Rightarrow$  New tool to locally probe strongly-interacting atomic gases
- Systematic large- $k$  expansions are possible
  - ✓ backward scattering  $\Rightarrow$  contact density
- Close connection to nuclear/particle physics

JLab, Science 320, 1476 (2008)



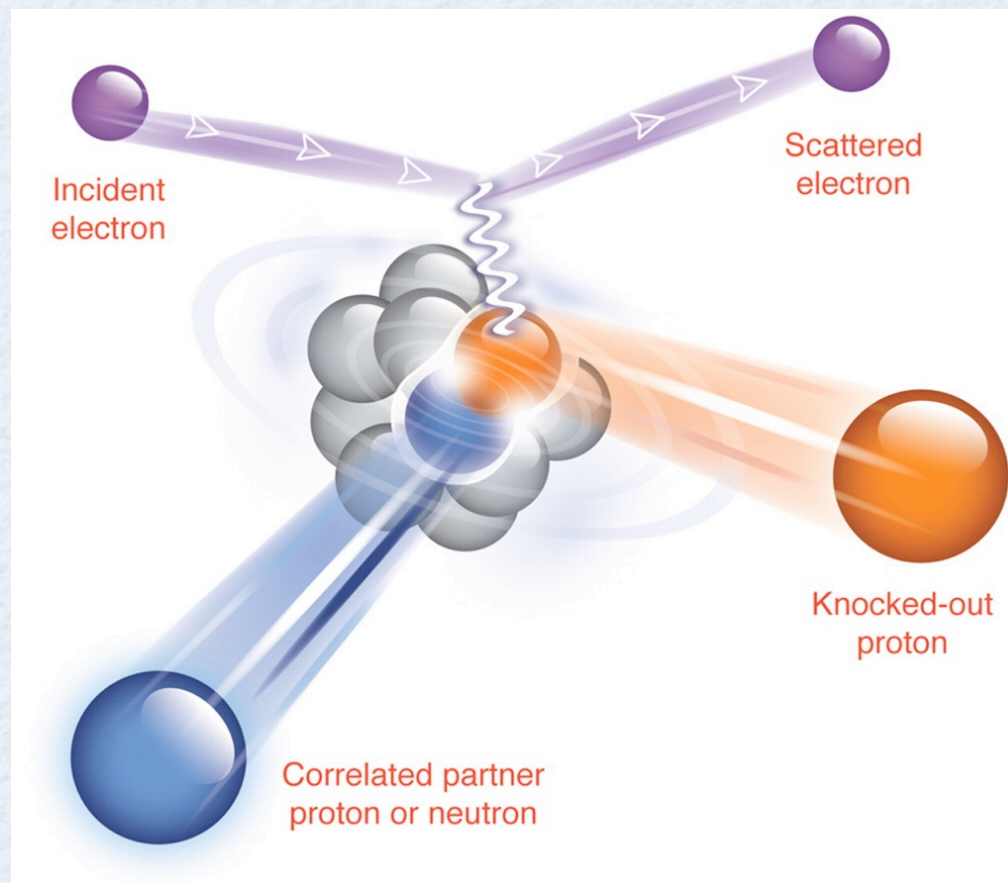


# Short summary 1

19/32

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- Systematic large- $k$  expansions are possible
  - ✓ backward scattering  $\Rightarrow$  contact density
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JLab, Science 320, 1476 (2008)



“Hard probes” are useful to reveal short-range pair correlations both in nuclei and atomic gases



**“Quark-hadron continuity”  
in cold atoms**



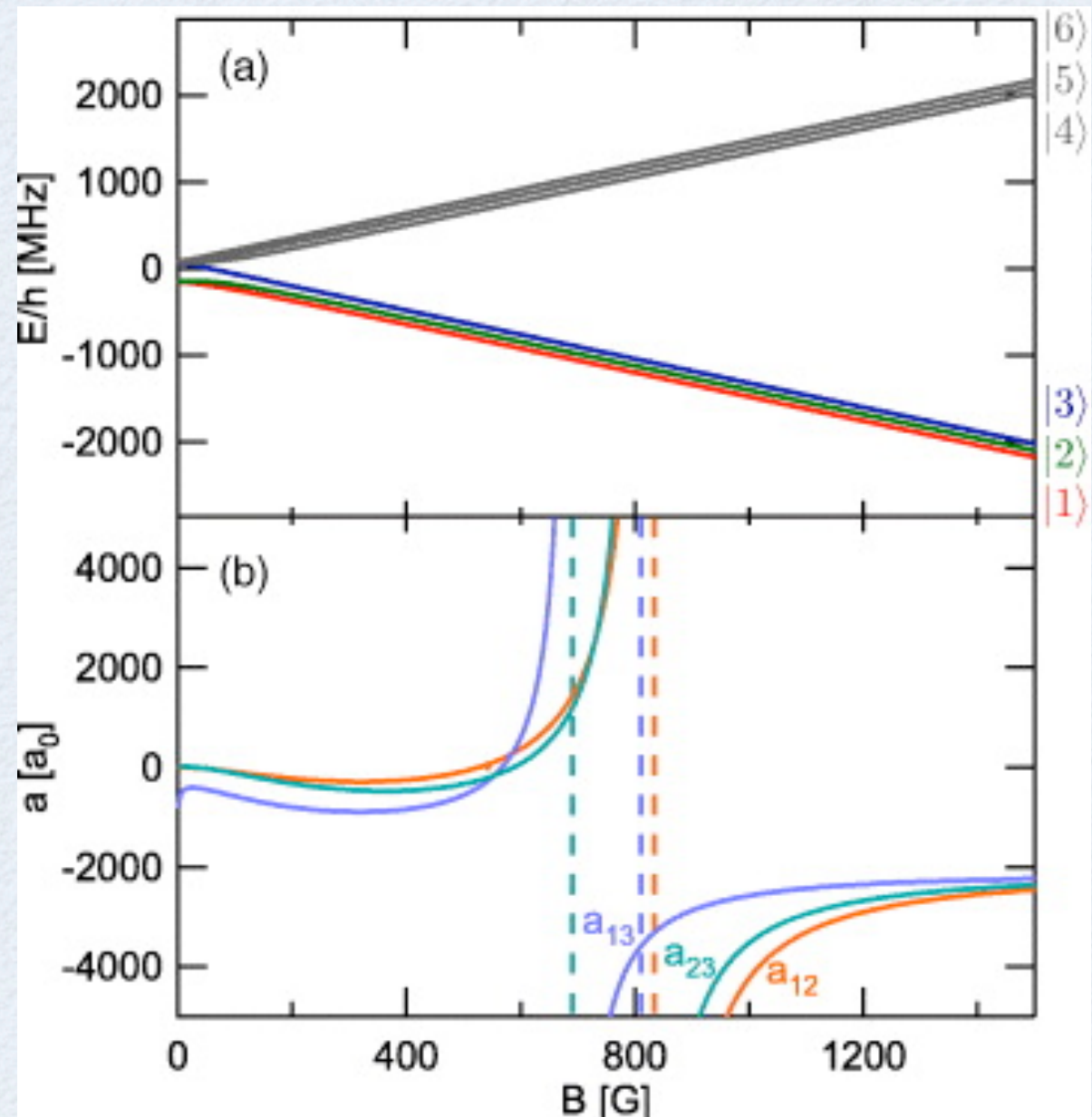
# 3-component Fermi gas

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- 3 spin states ( $i=1,2,3$ ) of  $^6\text{Li}$  atoms near a Feshbach resonance:

$$f(k) = \frac{-1}{ik + \frac{1}{a}}$$

- $a_{12} = a_{23} = a_{31}$





# 3-component Fermi gas

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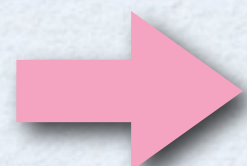
- 3 spin states ( $i=1,2,3$ ) of  $^6\text{Li}$  atoms near a Feshbach resonance:

$$f(k) = \frac{-1}{ik + \frac{1}{a}}$$

- $a_{12} = a_{23} = a_{31} \Rightarrow \text{SU}(3) \times \text{U}(1)$  invariance

$$\mathcal{L} = \psi_i^\dagger \left( i\partial_t + \frac{\nabla^2}{2m} \right) \psi_i + \frac{g}{2} \psi_i^\dagger \psi_j^\dagger \psi_j \psi_i$$

- **Problem !** 3 fermions form an infinitely deep bound state (**Thomas collapse**)



No many-body ground state :-)



# 3-component Fermi gas

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- 3 spin states ( $i=1,2,3$ ) of  ${}^6\text{Li}$  atoms near a “**narrow**” Feshbach resonance:

$$f(k) = \frac{-1}{ik + \frac{1}{a}} \quad \rightarrow \quad f(k) = \frac{-1}{ik + \frac{1}{a} + Rk^2}$$

$r_{\text{eff}} = -2R$  is the effective range

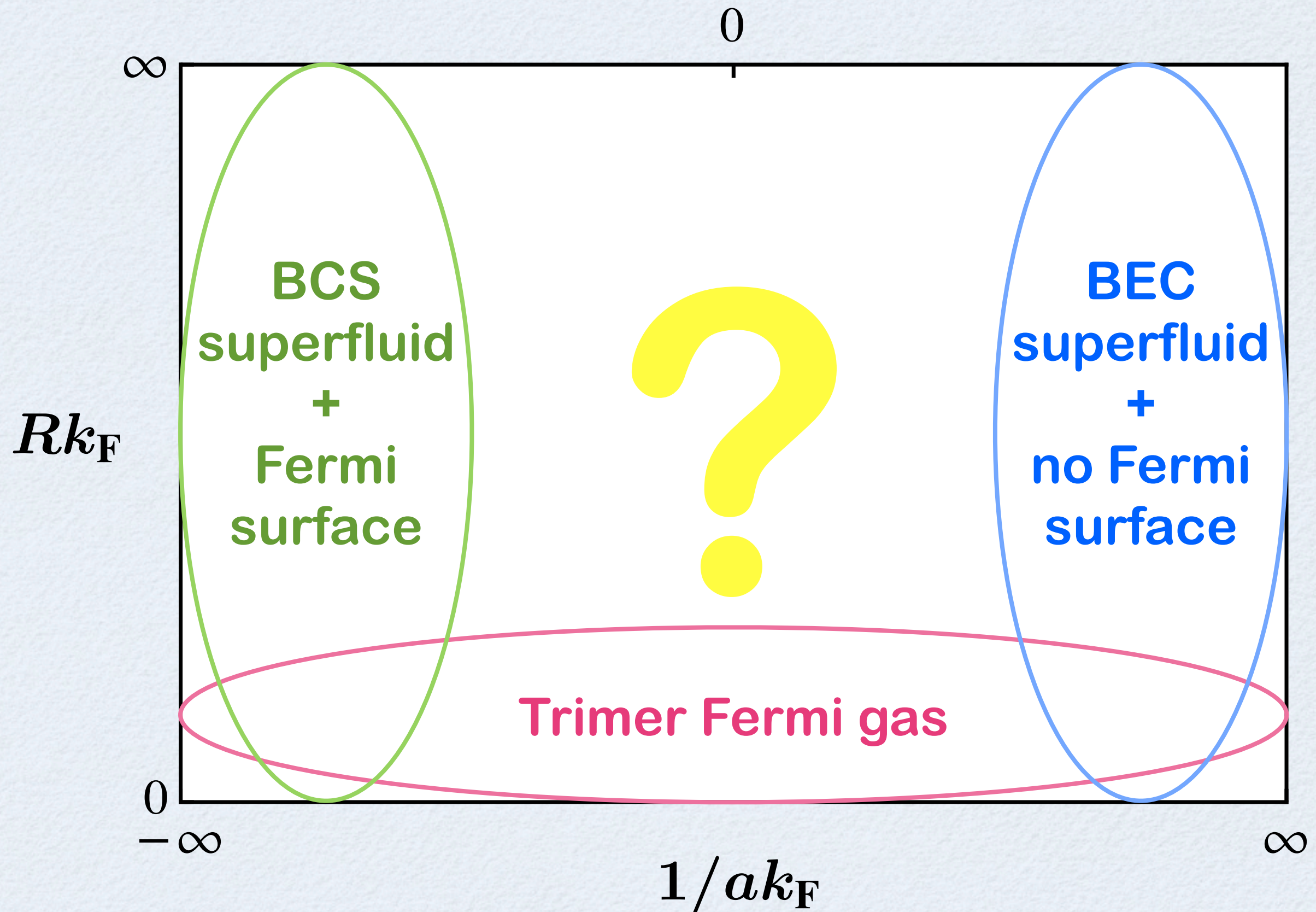
- $R$  regularizes ultraviolet behaviors  
( $\Rightarrow$  no Thomas collapse)

 **Universal many-body ground state**  
(depends only on  $a, R, k_F$ )



# Phase diagram

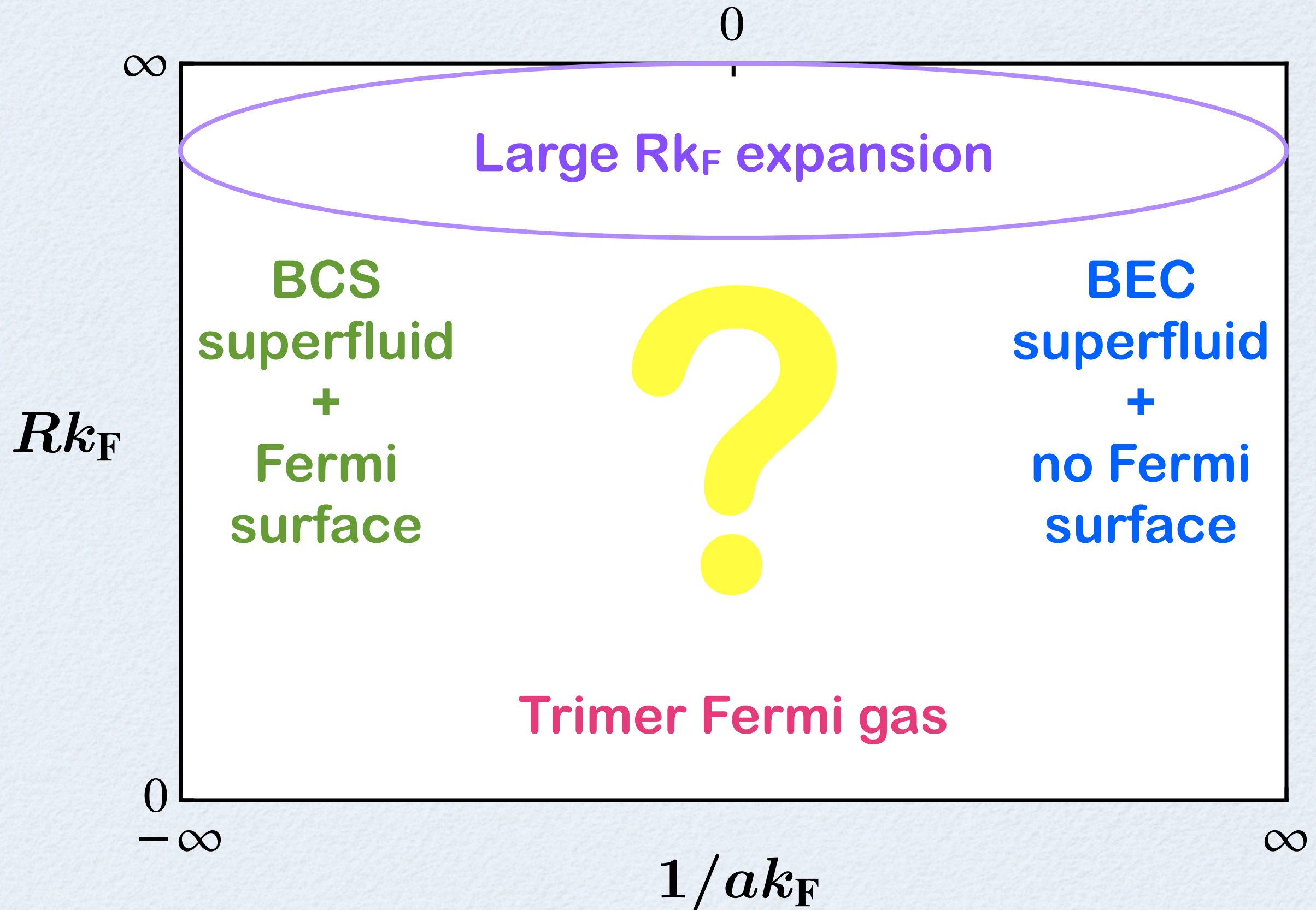
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# Phase diagram

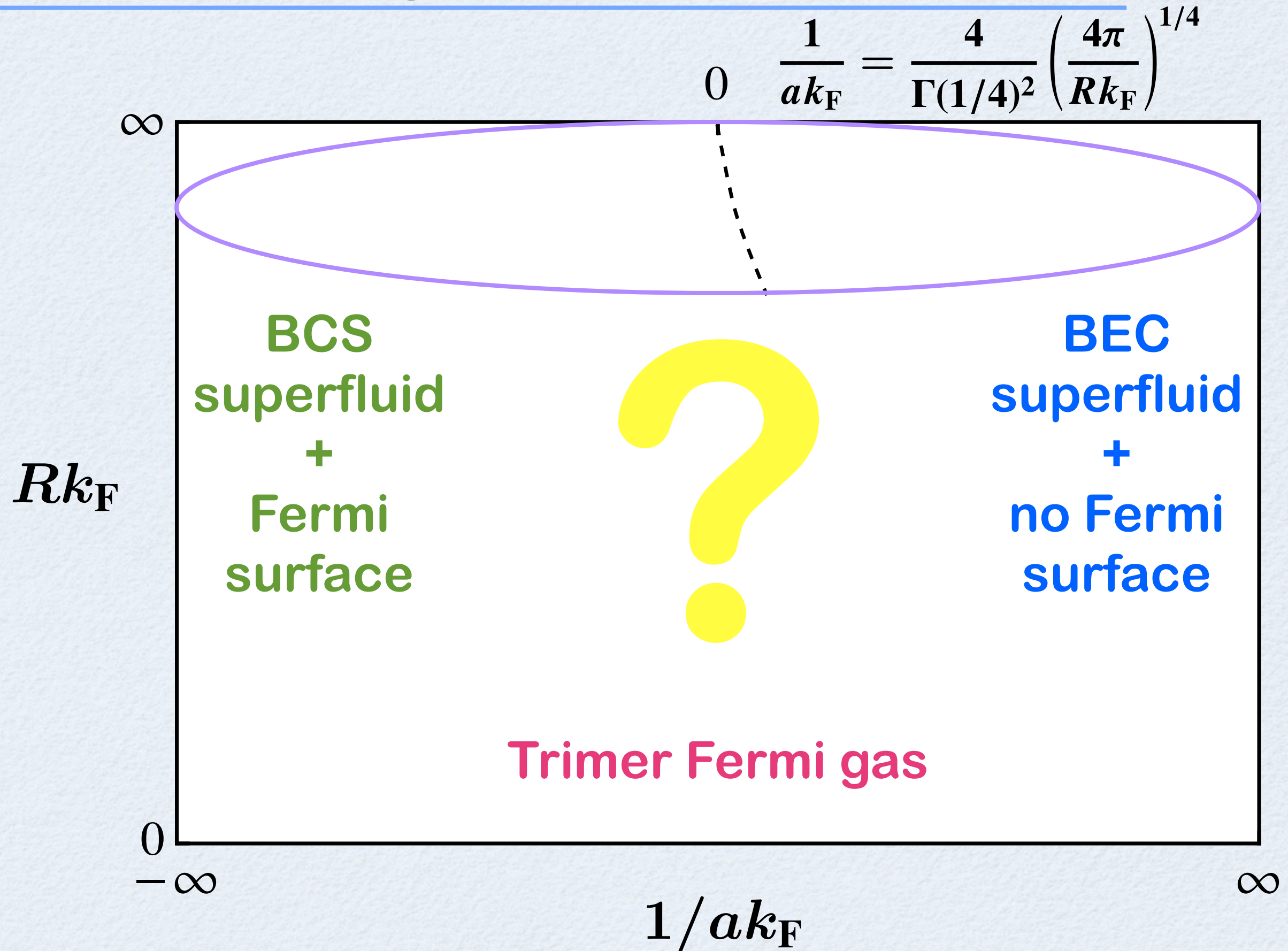
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# Phase diagram

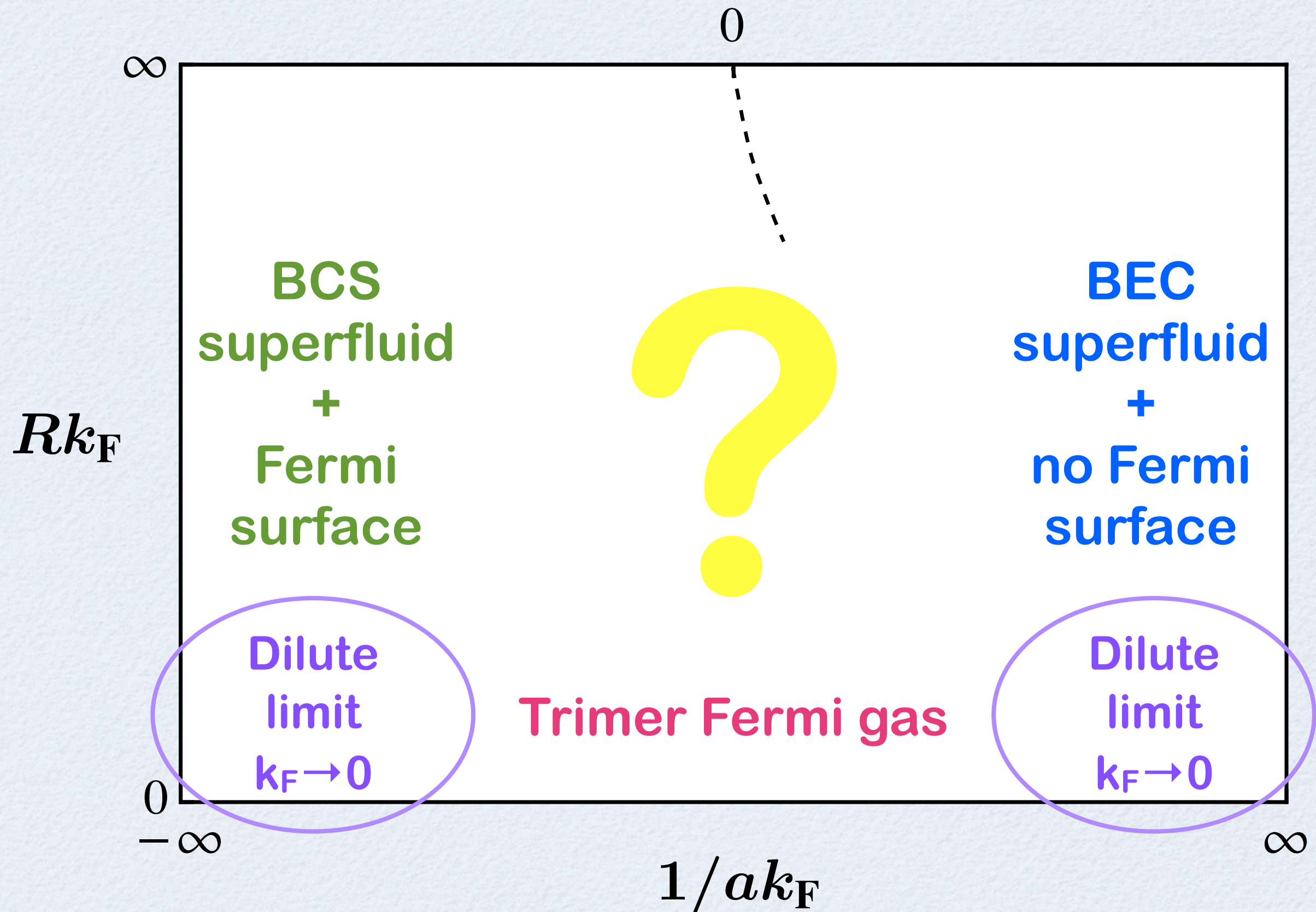
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# Phase diagram

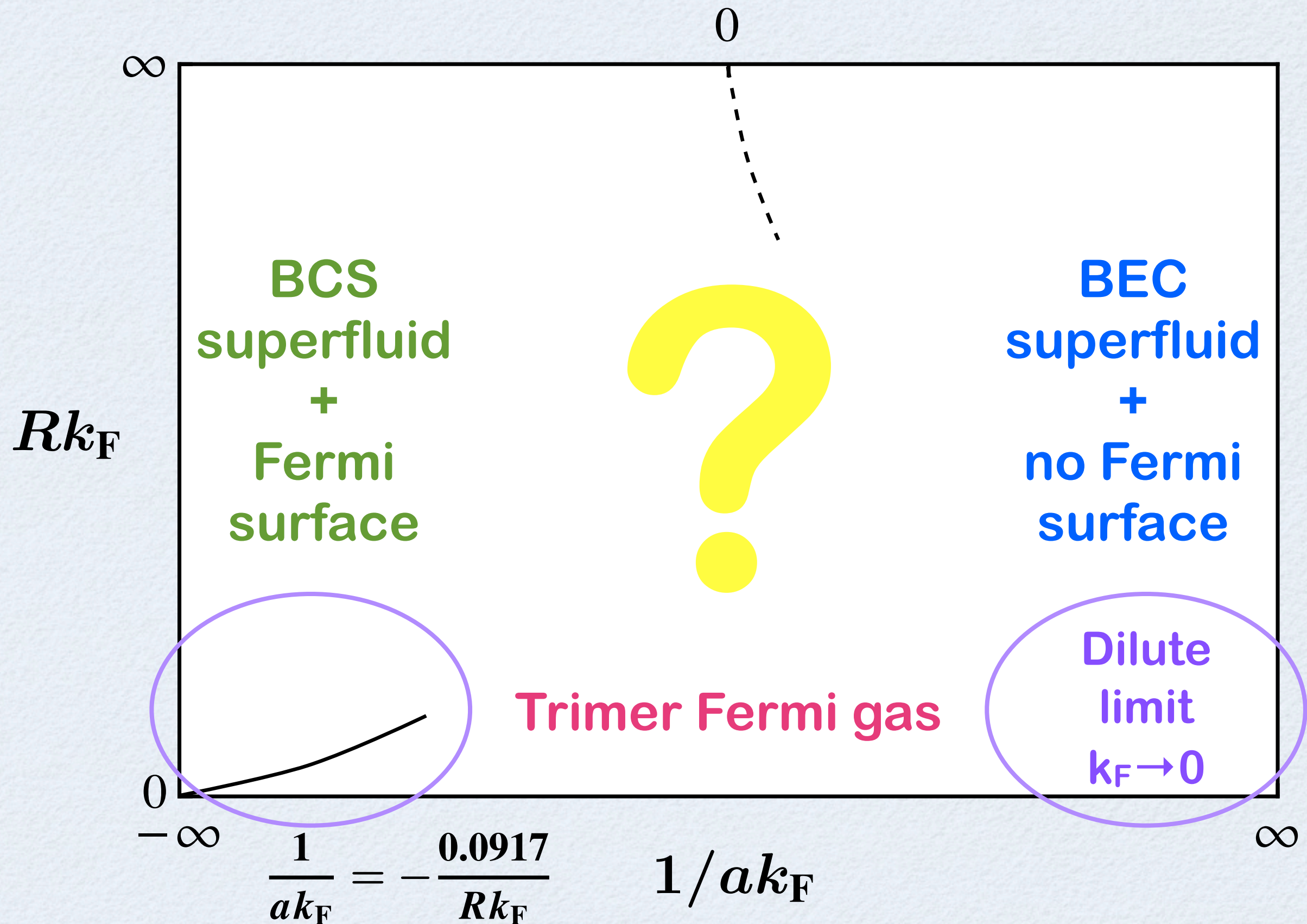
27/32





# Phase diagram

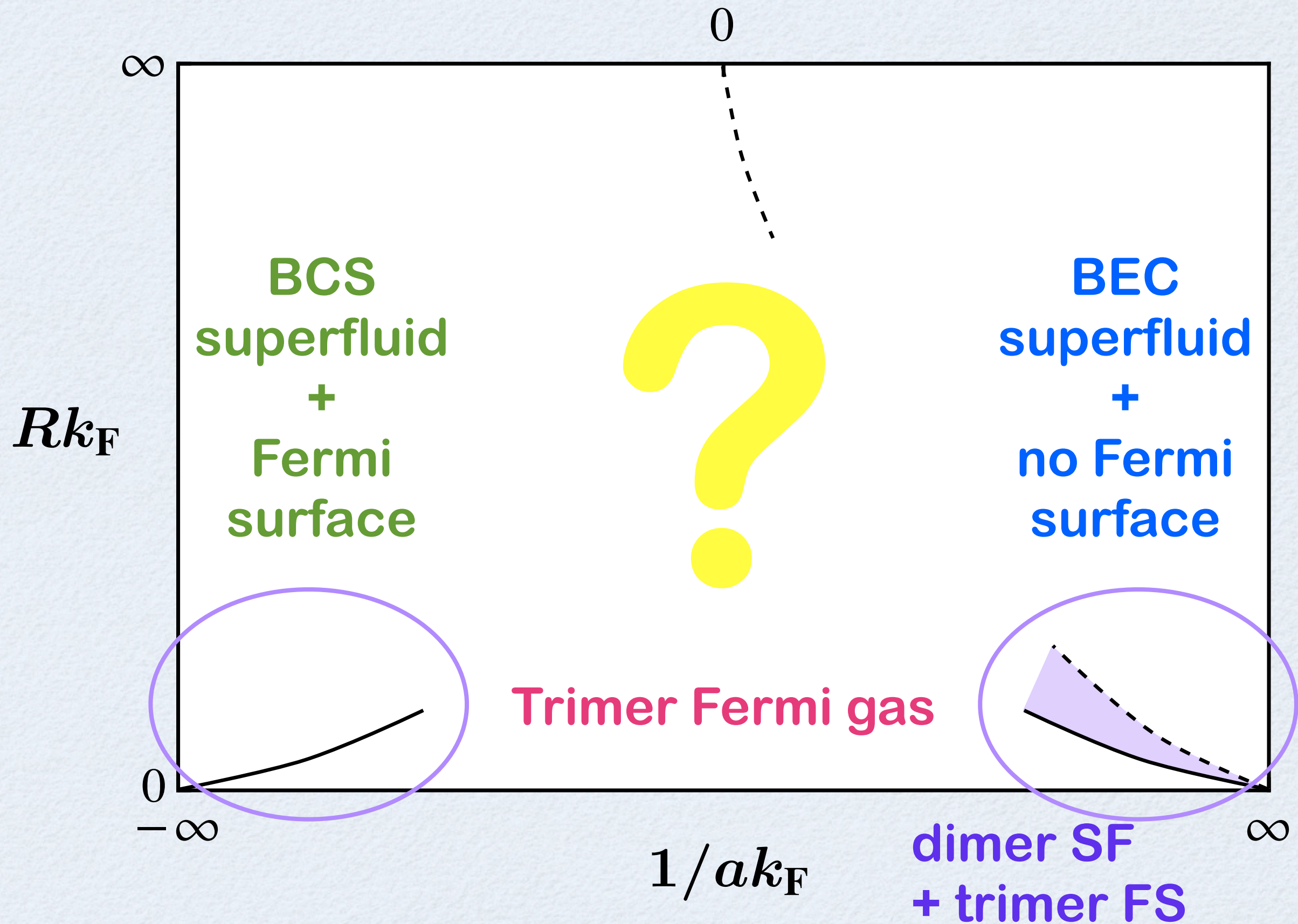
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# Phase diagram

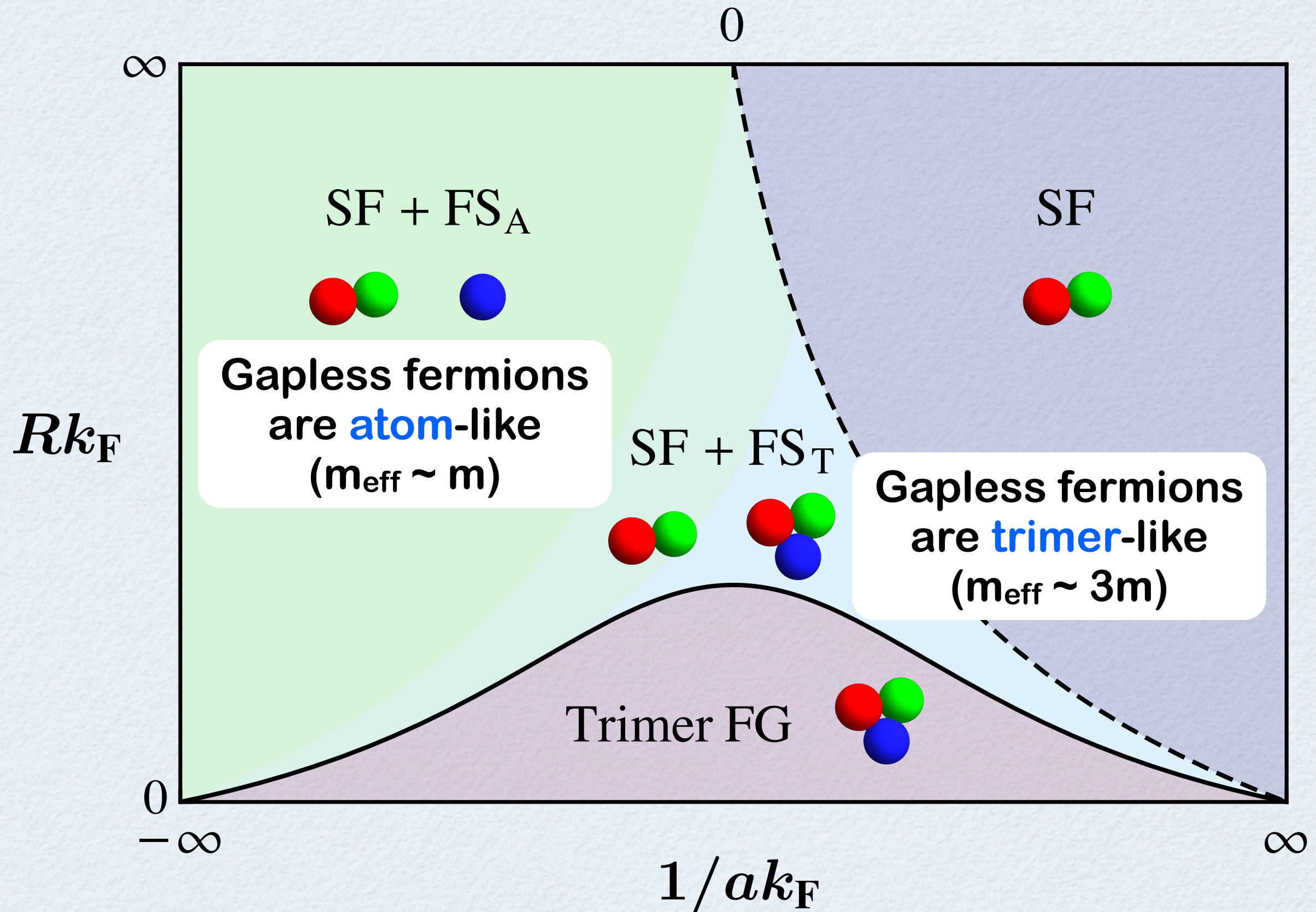
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# Phase diagram

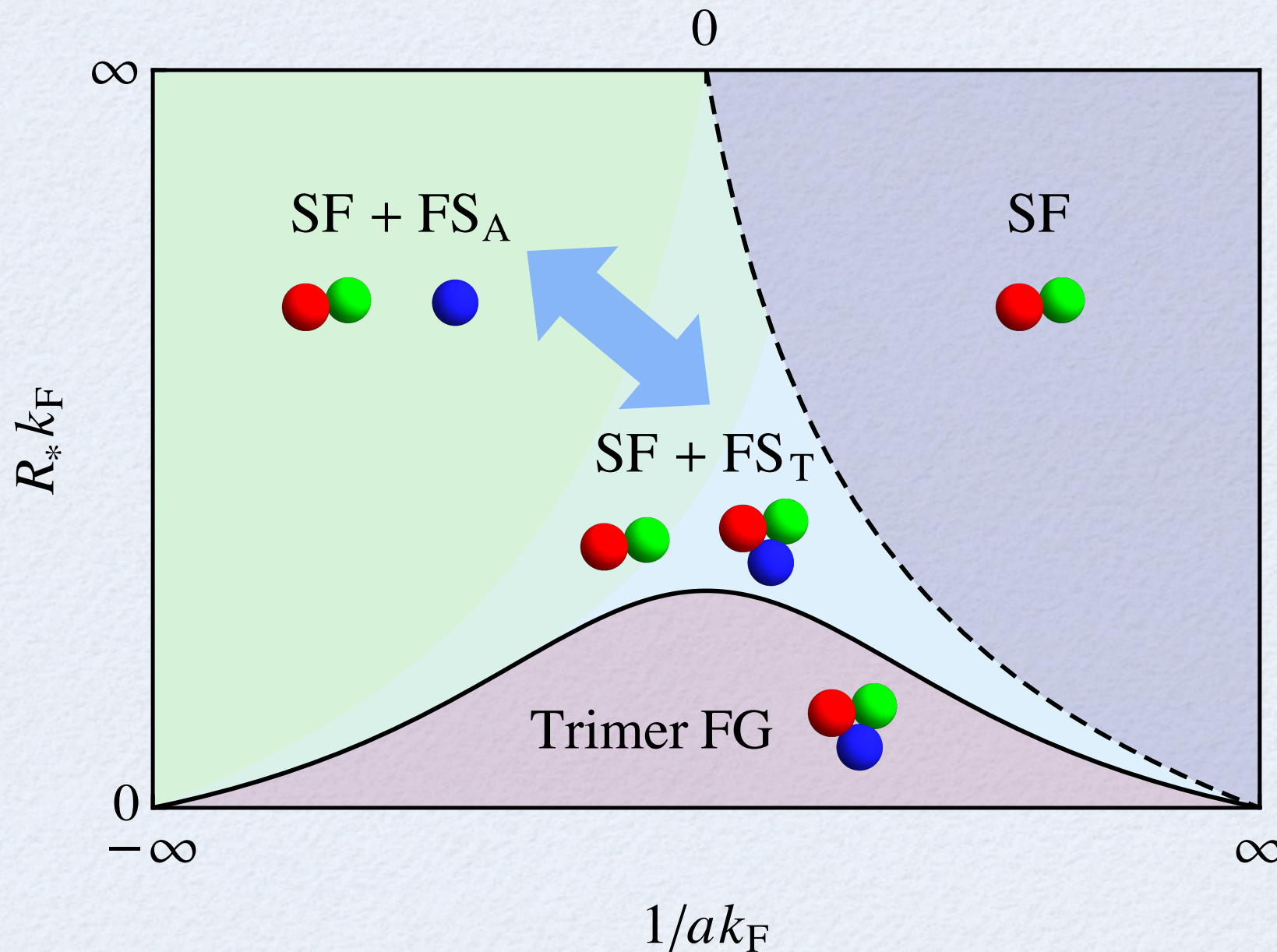
30 / 32



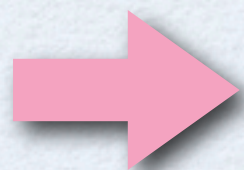


# “Atom-trimer” continuity

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“Atom-trimer continuity” seems to survive even when identical fermions form p-wave pairs



New analogy to extreme QCD ?



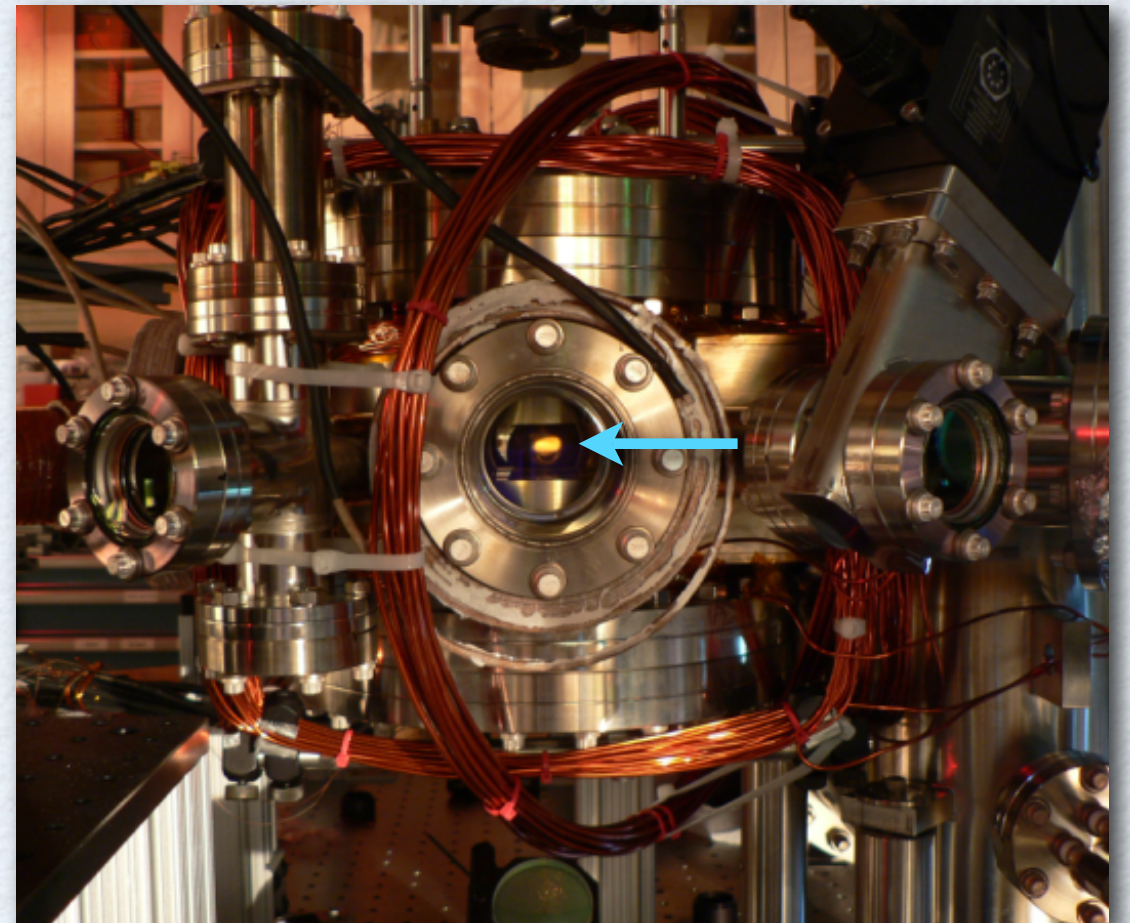
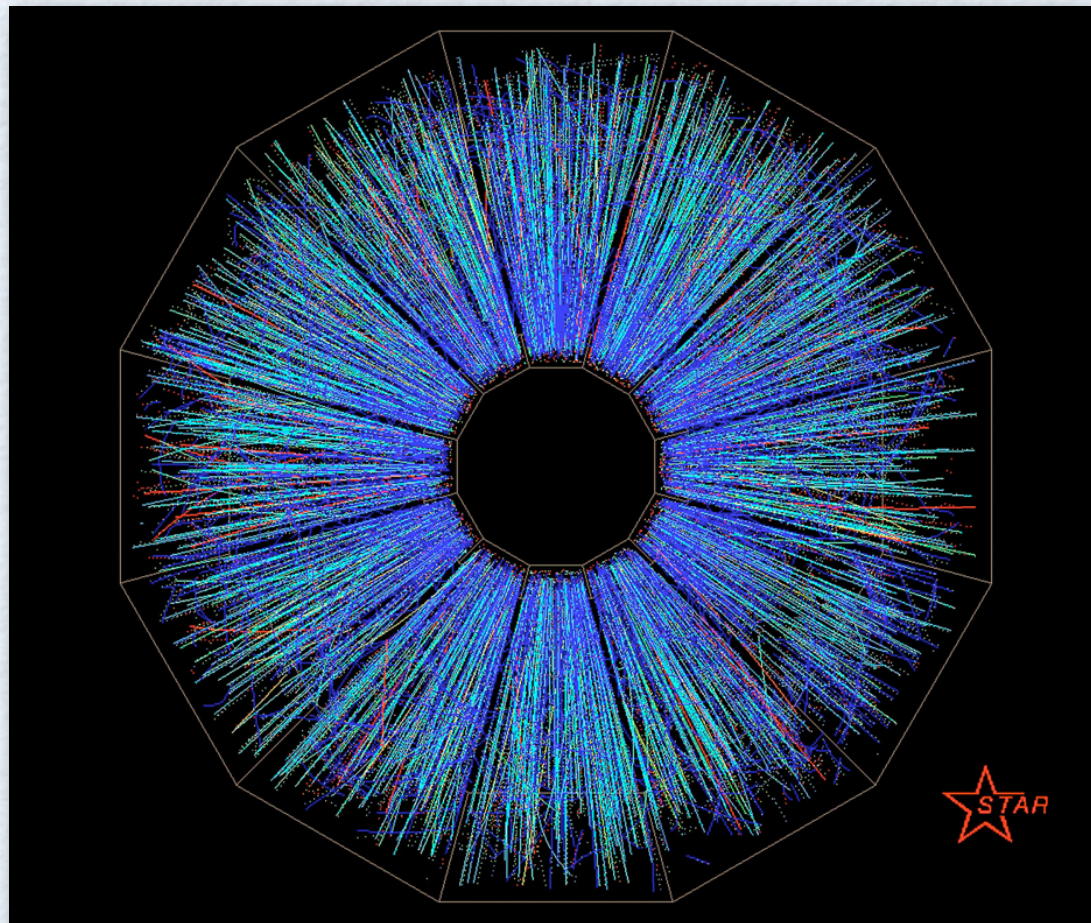
# Summary of this talk

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Extreme QCD



Ultracold atoms



New ideas wanted !